

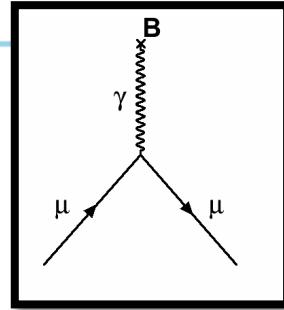
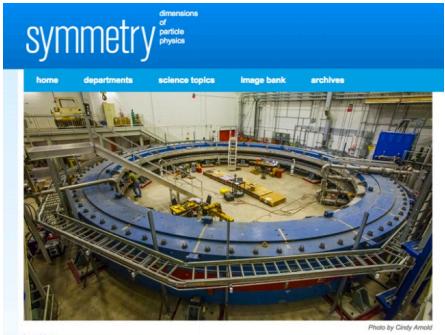
Muon g-2: Views from the Field



**Brendan Kiburg, Fermilab
(for the Muon g-2 Collaboration)
JETP Seminar
Jan 22, 2016**

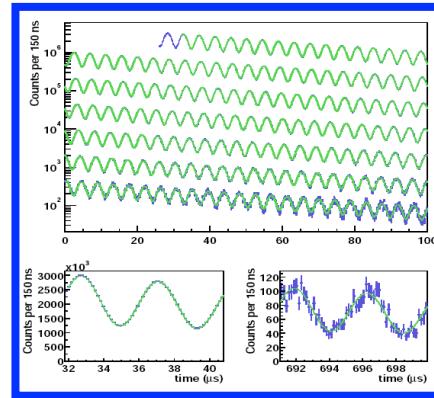
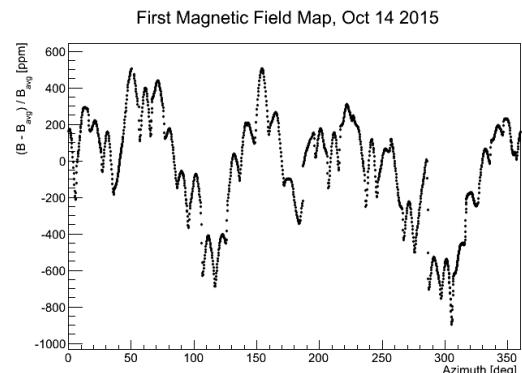
Outline

❖ Theoretical Background and Recent Progress



❖ Storage Ring Technique

❖ Experimental Progress and Details



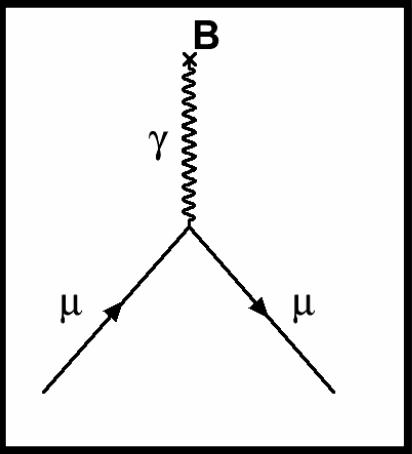
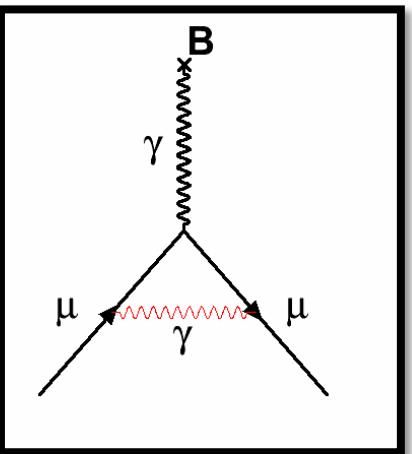
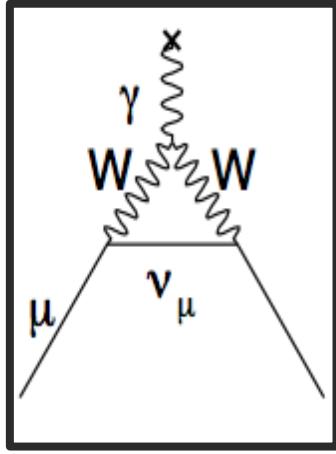
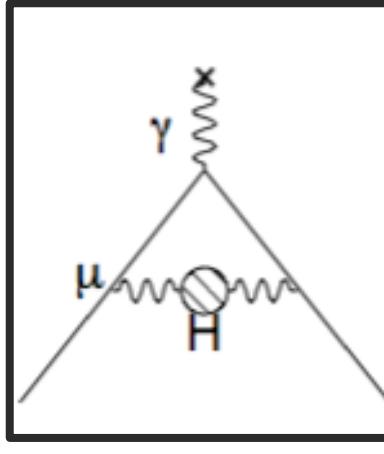
❖ Measurements from the Field

❖ Outlook



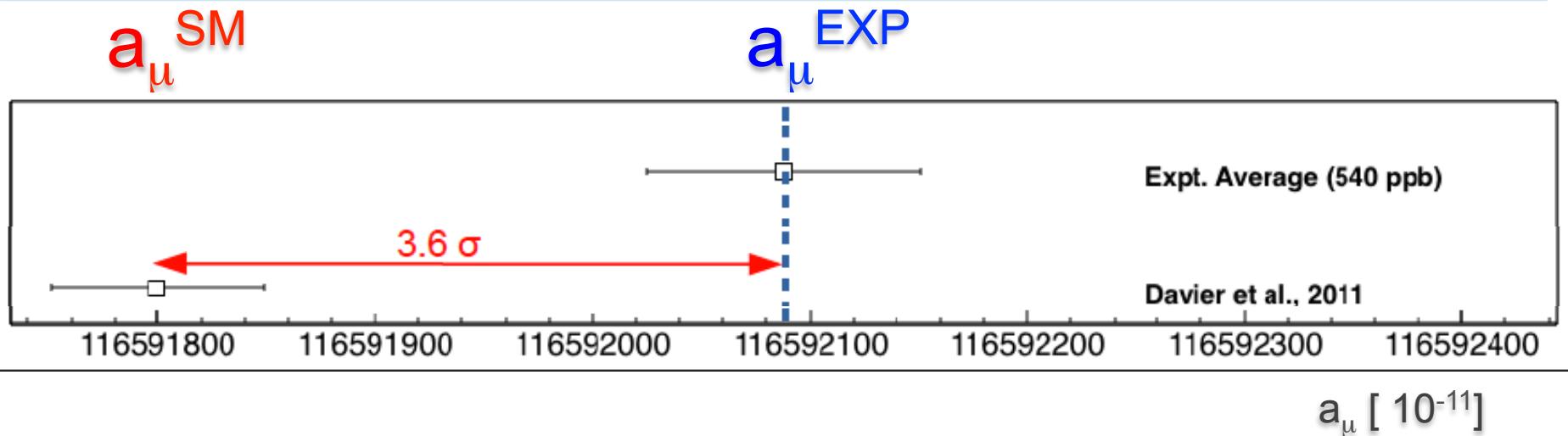
Muon g-2: The Basics

$$\vec{\mu} = g \frac{q}{2m} \vec{S}$$

$$g =$$

$$+$$

$$+$$

$$+$$

$$g = 2 + O(10^{-3})_{\text{QED}} + O(10^{-9})_{\text{EW}} + O(10^{-7})_{\text{QCD}}$$

$$a_\mu^{\text{SM}} = (g_\mu^{\text{SM}} - 2)/2 = a_\mu^{\text{QED}} + a_\mu^{\text{EW}} + a_\mu^{\text{QCD}}$$

Theory and Experiment Disagree



$$a_\mu^{\text{EXP}} - a_\mu^{\text{SM}} = ? = a_\mu^{\text{New Physics}}$$

New Physics or missing
systematics/statistics?

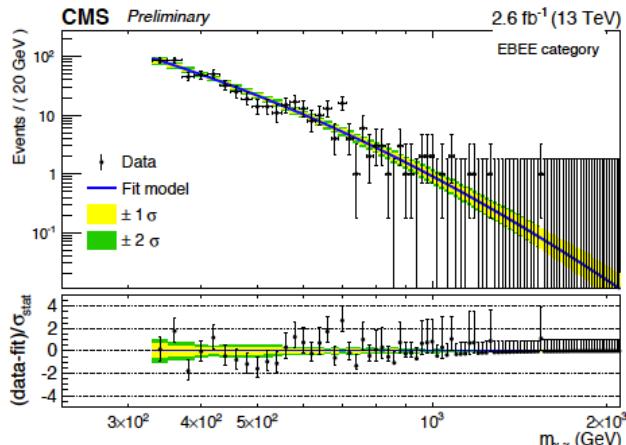
- ❖ Many Possible Models
- ❖ SUSY (many variations)
- ❖ Dark Photons
- ❖ Your model...

Explanations of new physics observations try to accommodate all the existing data

Exploring the unknown: CMS searches for new physics in 13 TeV data

Sergo Jindariani (Fermilab)

[http://theory.fnal.gov/jetp/talks/
WineAndCheese_2016-sergo.pdf](http://theory.fnal.gov/jetp/talks/WineAndCheese_2016-sergo.pdf)



[https://cds.cern.ch/record/2114808/files/
EXO-15-004-pas.pdf](https://cds.cern.ch/record/2114808/files/EXO-15-004-pas.pdf)

Hints of 750 GeV resonance ($O(2\sigma)$)

125 GeV Higgs ($>5\sigma$)

Muon g-2 ($>3\sigma$)

no new sparticles...

arXiv.org > hep-ph > arXiv:1512.06715

High Energy Physics – Phenomenology

750 GeV Diphoton Resonance, 125 GeV Higgs and Muon g-2 Anomaly in Deflected Anomaly Mediation SUSY Breaking Scenario

Fei Wang, Lei Wu, Jin Min Yang, Mengchao Zhang

(Submitted on 21 Dec 2015)

arXiv.org > hep-ph > arXiv:1512.07212

High Energy Physics – Phenomenology

750 GeV resonance in the Dark Left-Right Model

Ujjal Kumar Dey, Subhendra Mohanty, Gaurav Tomar

(Submitted on 22 Dec 2015)

arXiv.org > hep-ph > arXiv:1511.07447

High Energy Physics – Phenomenology

Z' models for the LHCb and g-2 muon anomalies

Ben Allanach, Farinaldo S. Queiroz, Alessandro Strumia, Sichun Sun

(Submitted on 23 Nov 2015)

We revisit a class of Z' explanations of the anomalies found by the LHCb collaboration in B decays, and show that the scenario is tightly constrained by a combination of constraints: (i) LHC searches for di-muon resonances, (ii) perturbativity of the Z' couplings; (iii) the B_s mass difference, and (iv) and electro-weak precision data. Solutions are found by suppressing the Z' coupling to electrons and to light quarks and/or by allowing for a Z' decay width into dark matter. We also present a simplified framework where a TeV-scale Z' gauge boson that couples to standard leptons as well as to new heavy vector-like leptons, can simultaneously accommodate the LHCb anomalies and the muon g-2 anomaly.

Comments: 10 pages, 11 figures

Subjects: High Energy Physics – Phenomenology (hep-ph)

Report number: CETUP2015-028

Cite as: arXiv:1511.07447 [hep-ph]

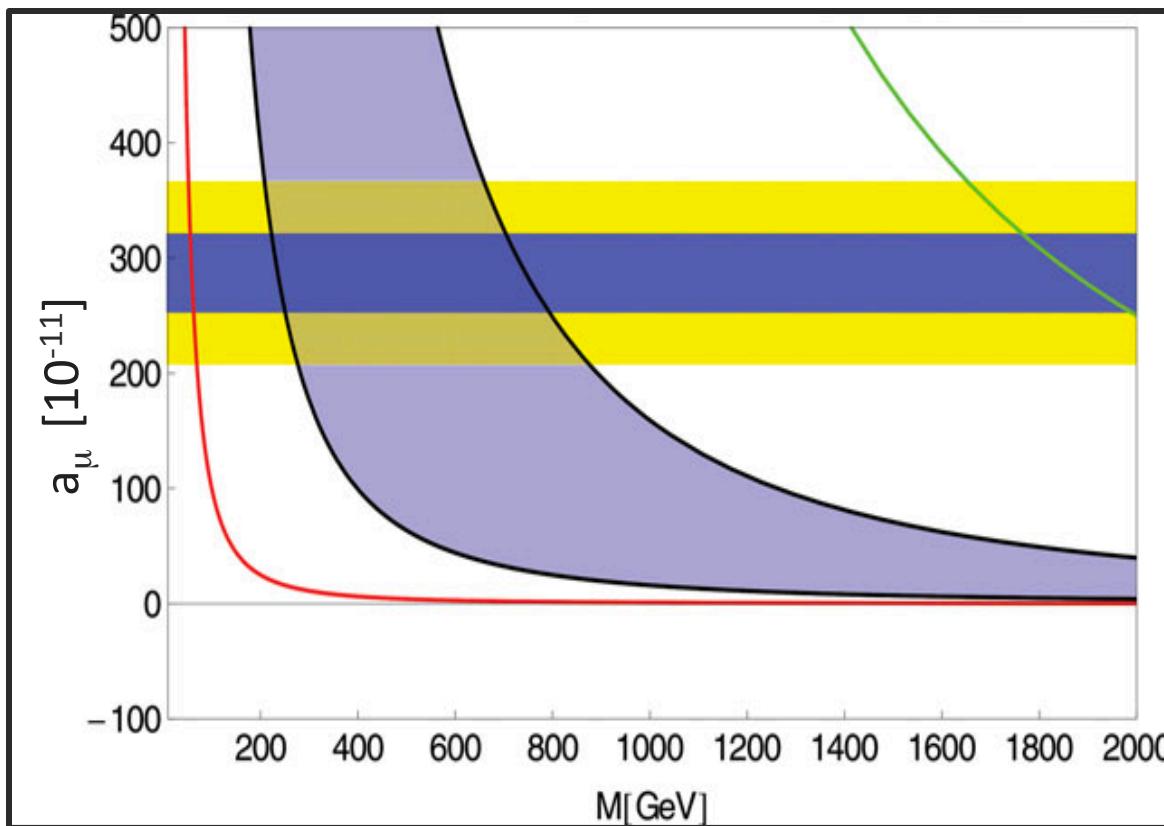
New Physics: TeV Scale Models

Z', W', UED, Littlest Higgs
(assumes typical weak coupling)

Radiative muon mass Generation



Unparticles, Extra Dimension
Models, SUSY ($\tan\beta = 5$ to 50)

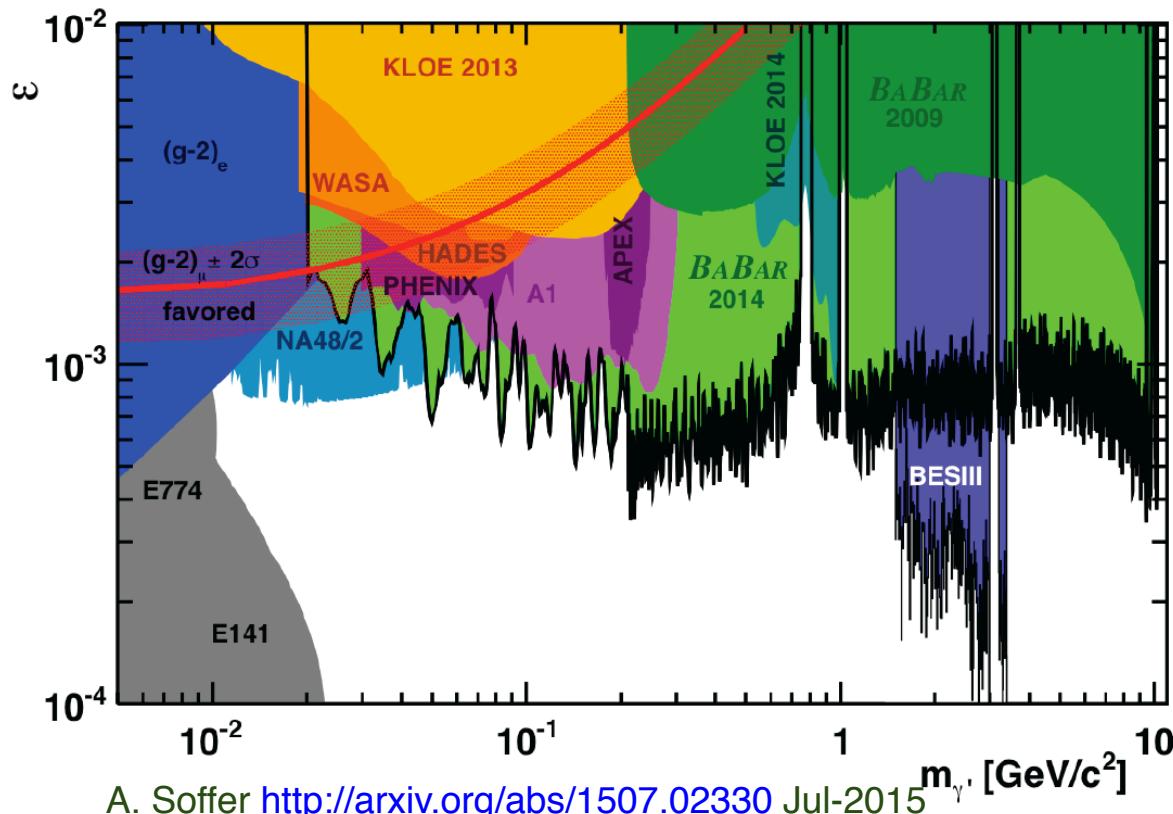
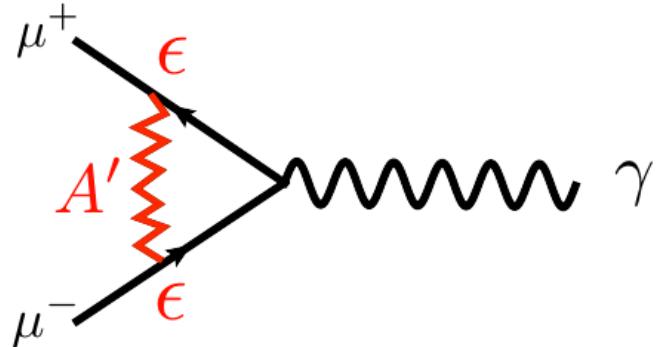
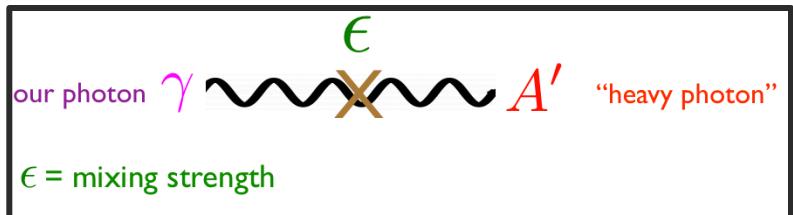


- Improved Precision will continue to constrain (or possibly validate!) the energy scale of the models

D. Hertzog, Ann. Phys (Berlin) 2015., courtesy D. Stockinger

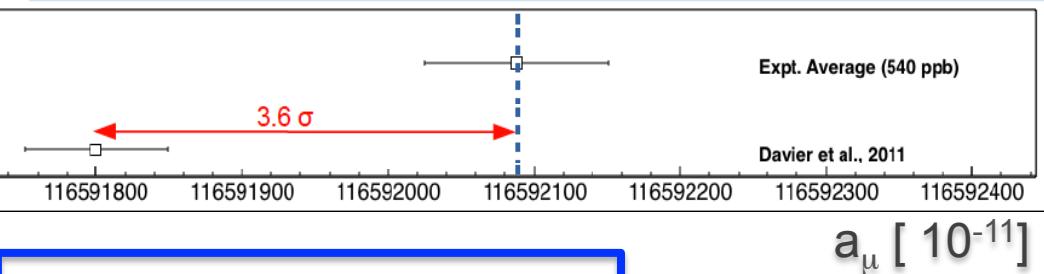
New Physics Possibilities: Essig's W&C Jan-2012

- A new U(1)' symmetry
- Dark Photon A'



A. Soffer <http://arxiv.org/abs/1507.02330> Jul-2015

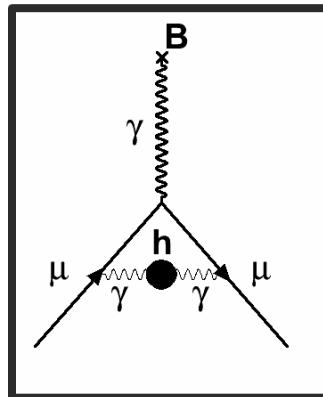
The discrepancy needs further study (validation/refutation)



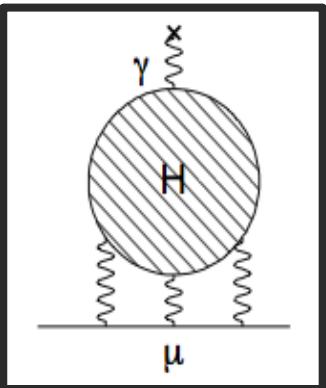
Leading contribution to a_μ

Leading contribution to δa_μ

Hadronic Vacuum Polarization (HVP)



Hadronic Light-By-Light(HLbL)



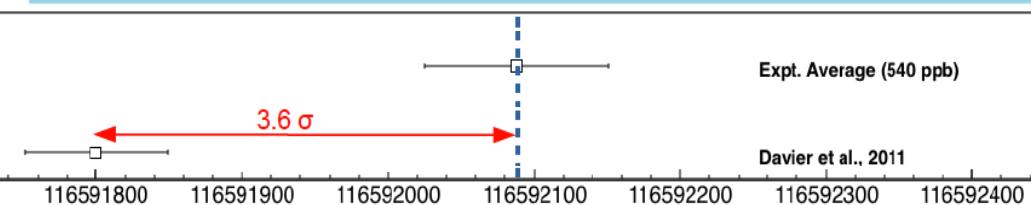
Contribution	a_μ Cont. ($\times 10^{-11}$)	Uncertainty ($\times 10^{-11}$)
QED ($\gamma + I$)	116 584 718.951	± 0.1
HVP (lo)	6 949	± 43
HVP (ho)	-98.4	± 0.7
HLbL	105	± 26
EW	154	± 1
Total SM	116 591 828	± 50

- e^+e^- colliders
 $\rightarrow \delta a_\mu^{\text{HVP}} \sim 0.7\%$
- $\delta a_\mu^{\text{HVP}} \sim 5\%$ 2013
- Lattice progress at the physical π mass
- Goal 1-2% level within a few years (e^+e^- check)
- The future

- Model dep ($\sim 25\%$)
- New dispersive calculation approach
- Extend Lattice
 - Finite Volume
 - Disconnected diagrams
- Blum et al. optimistic

Reproduced from Blum et al. <http://arxiv.org/pdf/1311.2198v1.pdf>, Nov 2013

The discrepancy needs further study (validation/refutation)



Hadronic Vacuum Polarization (HVP)

Hadronic Light-By-Light(HLbL)

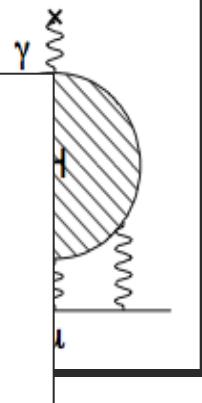
INT Program INT-15-3

Leading contrib

Intersections of BSM Phenomenology and QCD for New Physics Searches

September 14 - October 23, 2015

Seminars



Leading contrib

Contribution	a_μ^{QCD}	Date	Speaker	Title
QED ($\gamma + I$)	116	September 29, 2015	B. Kiburg	"Muon g-2 Experimental Update" "Video of recent experimental progress"
HVP (lo)		September 29, 2015	C. Davies	"HVP contribution to the muon anomalous magnetic moment from lattice QCD"
HVP (ho)	Q	September 29, 2015	T. Blum	"Progress on computing the hadronic light-by-light scattering contribution to the muon anomalous magnetic moment from lattice QCD(+QED)"
EW		September 29, 2015	M. Hoferichter	"Hadronic light-by-light scattering in the muon g - 2: a dispersive approach"
Total SM				

ρ (~25%)
dispersive
n

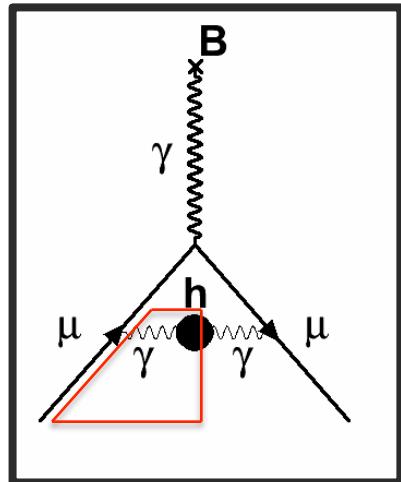
lattice
Volume
connected
ms
I.

Reproduced from Blum et al. <http://arxiv.org/pdf/1311.2198v1.pdf>, Nov 2013

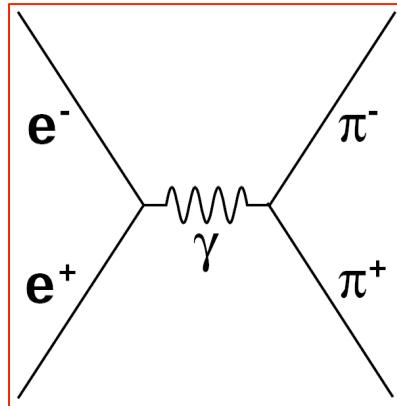


Critical inputs to the Hadronic Vacuum Polarization Calculation

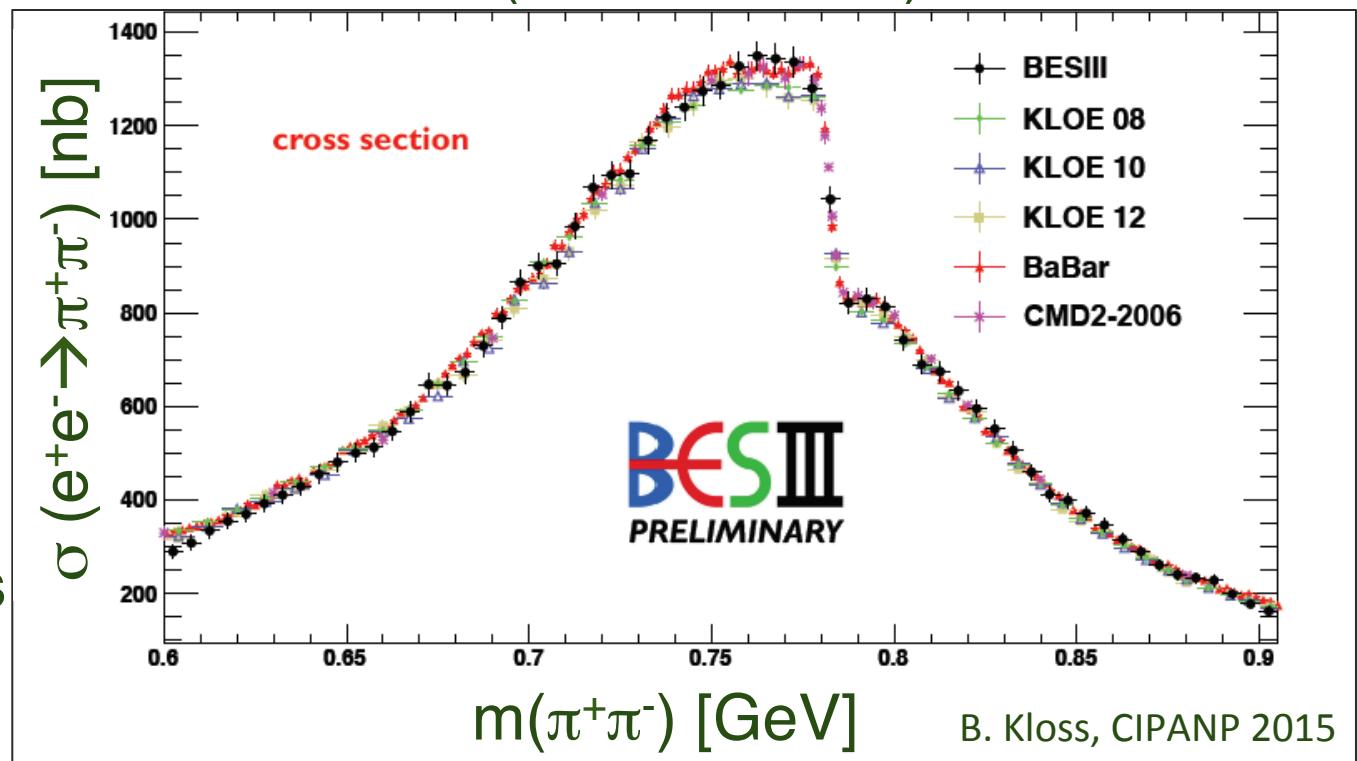
HVP



$e^+e^- \rightarrow \text{hadrons}$



σ (600-900 MeV)



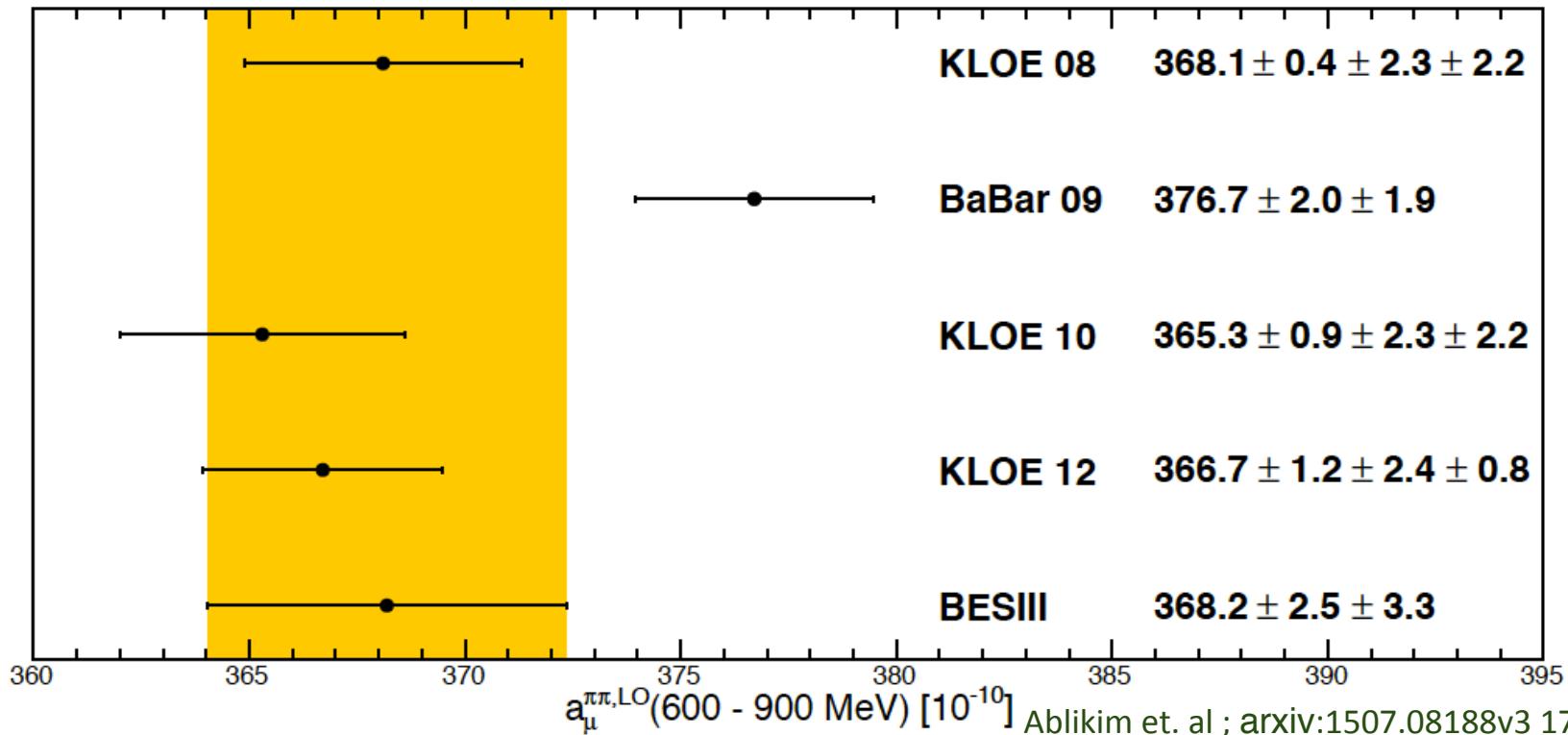
B. Kloss, CIPANP 2015

Dispersion Relation for a_μ

$$a_\mu^{\text{HVP}} \cong \frac{1}{4\pi^3} \int_{4m_\pi^2}^\infty K(s) \sigma(e^+e^- \rightarrow \text{hadrons}) ds$$

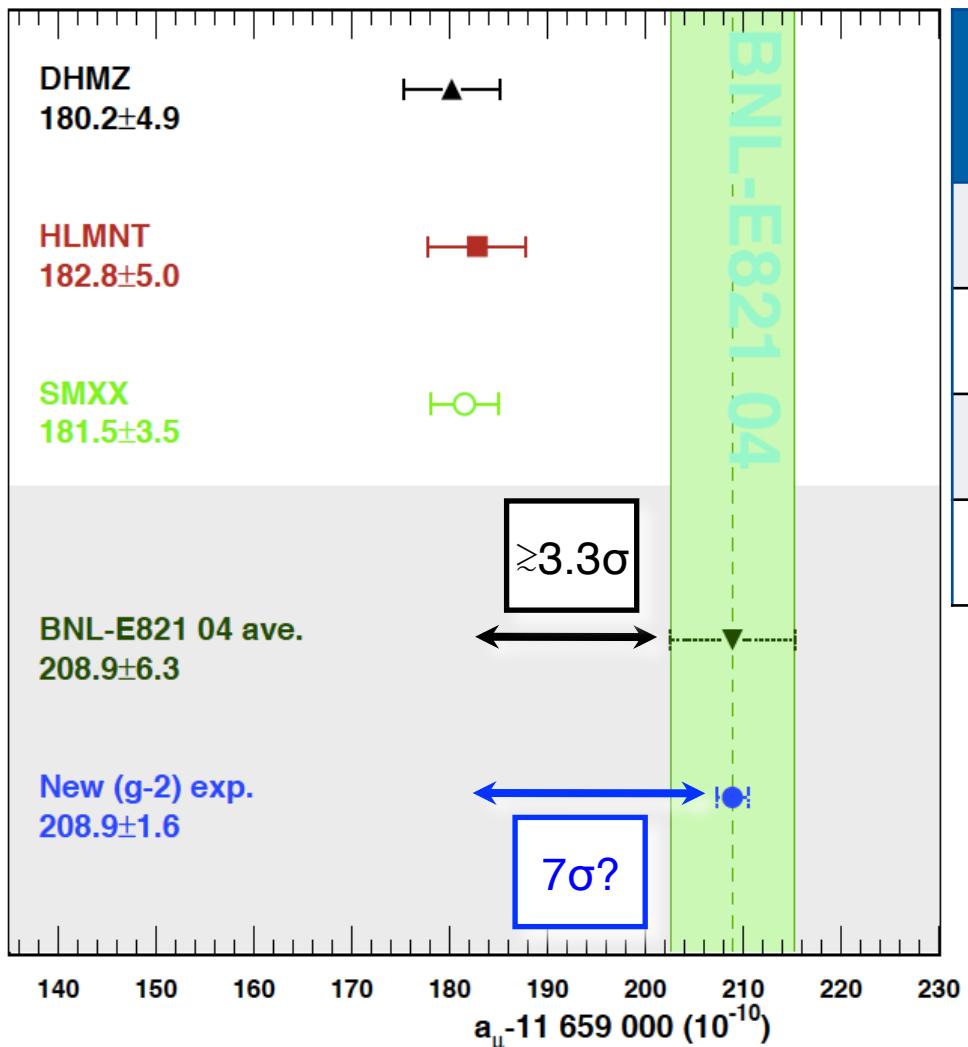
Kernel function $K(s) \propto \frac{1}{s}$

e^+e^- machine data continues to reduce δa_μ^{SM}



- $\delta a_\mu^{\text{HVP}}/a_\mu^{\text{HVP}} (\sim 0.7\%)$
- BES-III: 3x more data available, luminosity measurement improvements
- VEPP-2000 : Aiming for 0.3% fractional uncertainty by 2017
 - Radiative return plus Energy scan

More precise comparison of SM and experimental values of g-2 needed to reveal new physics



Uncertainty Source δa_μ Status 2015 [ppb]	Projected after E989 [ppb]
Total Theory	420
HVP	360
HLbL	225
Total Exp.	540
	140

[Blum et al., arXiv:1311.2198]

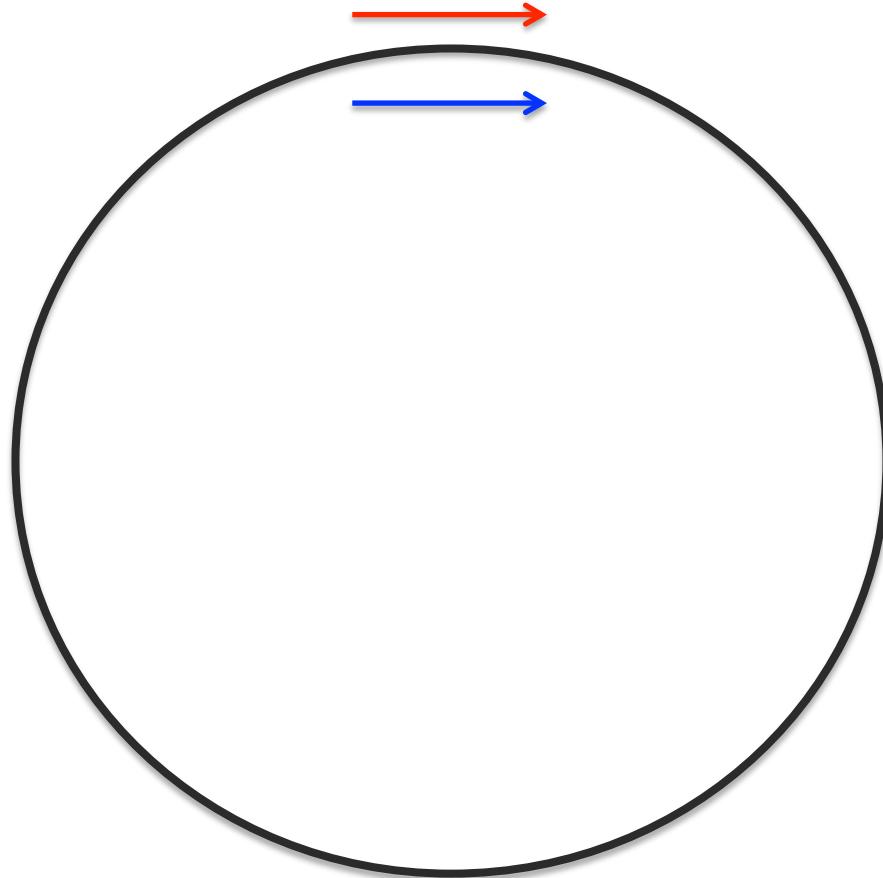


STORAGE RING TECHNIQUE

Experiment Basics: Muons in a storage ring

→ momentum
→ spin

1. Start with polarized muon beam (from pion decay)



Experiment Basics: Muons in a storage ring

→ momentum
→ spin

1. Start with polarized muon beam (from pion decay)

2. Cyclotron frequency :

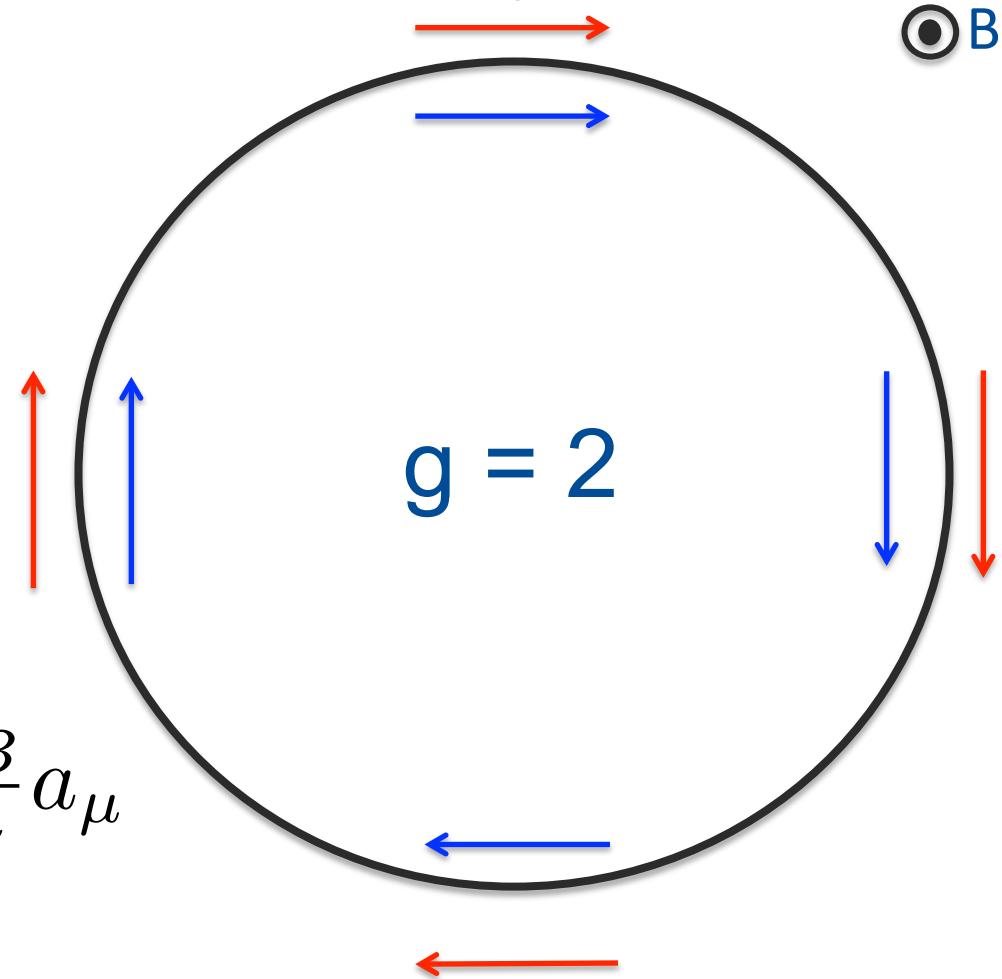
$$\omega_c = \frac{e}{m\gamma} B$$

3. Spin precession frequency :

$$\omega_S = \frac{e}{m\gamma} B (1 + \gamma a_\mu)$$

Larmor + Thomas
precession

$$\omega_a = \omega_S - \omega_c = \frac{eB}{m} a_\mu$$



Experiment Basics: Muons in a storage ring

→ momentum
→ spin

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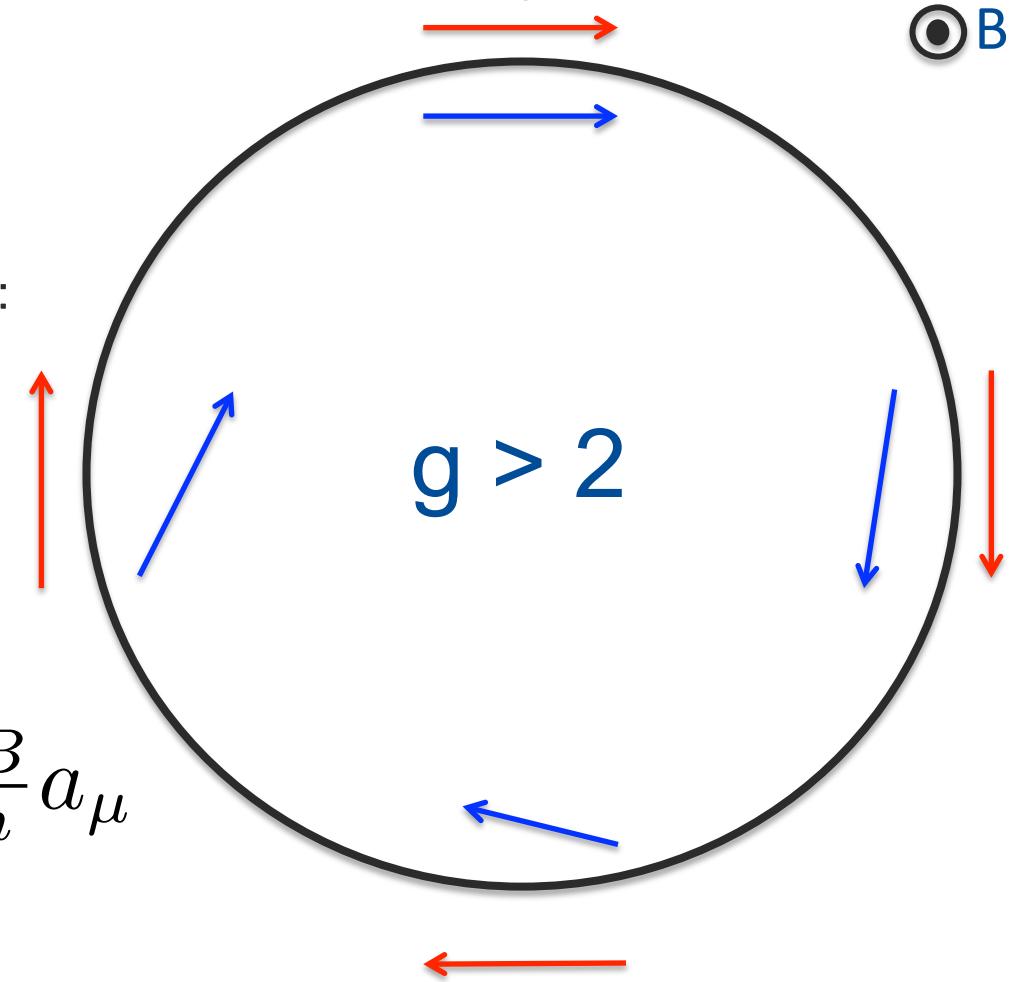
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precession

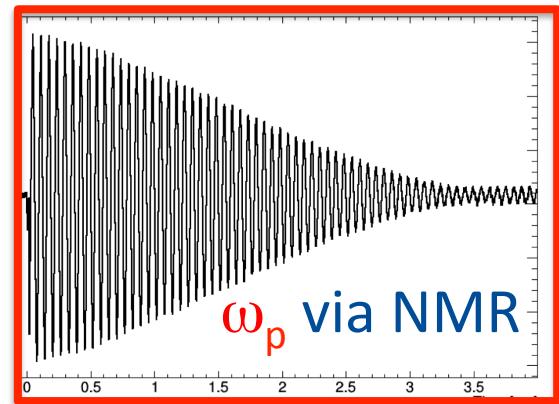
$$\omega_a = \omega_S - \omega_c = \frac{eB}{m} a_\mu$$



Muon g-2 Measurements

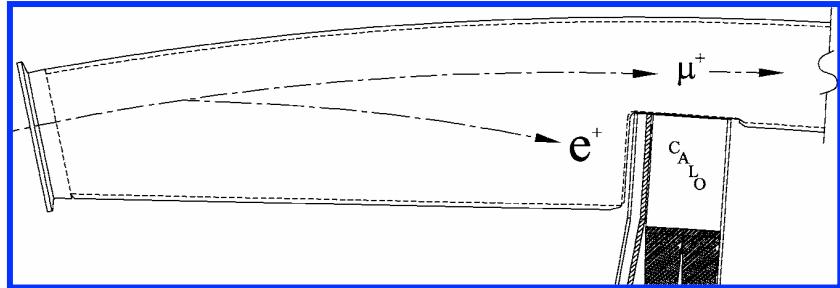
$$\omega_a = \frac{eB}{m} a_\mu$$

Measure B → via NMR →
recast a_μ in terms of proton
precession frequency, ω_p

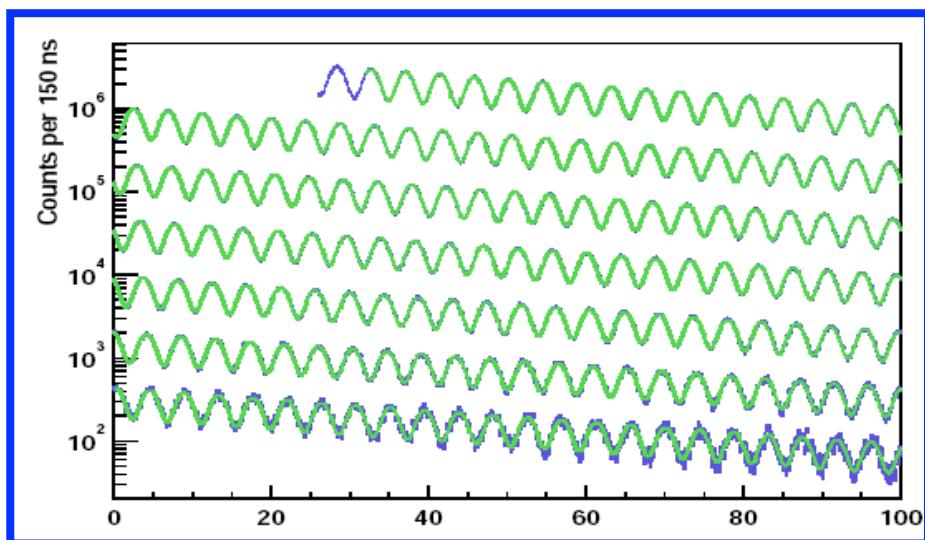


$$a_\mu = \frac{\omega_a / \omega_p}{\mu_\mu / \mu_p - \omega_a / \omega_p}$$

Muon spin precession frequency



E821 data: e^+ with $E > 1.8$ GeV



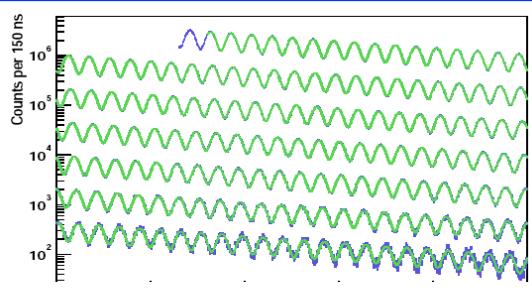
$$\omega_a = \omega_S - \omega_c = \frac{eB}{m} a_\mu$$

- Decay self-analyzing:
 - Higher energy positrons emitted preferentially in direction of muon spin

$$N(t) = N_0 e^{-t/\tau} (1 + A \cos(\omega_a t + \phi))$$

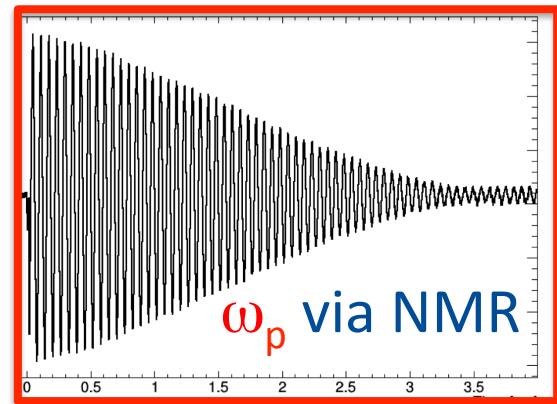
- Spectrum distortions from
 - Pileup, gain stability
 - Beam Effects, Losses

Muon g-2 Measurements



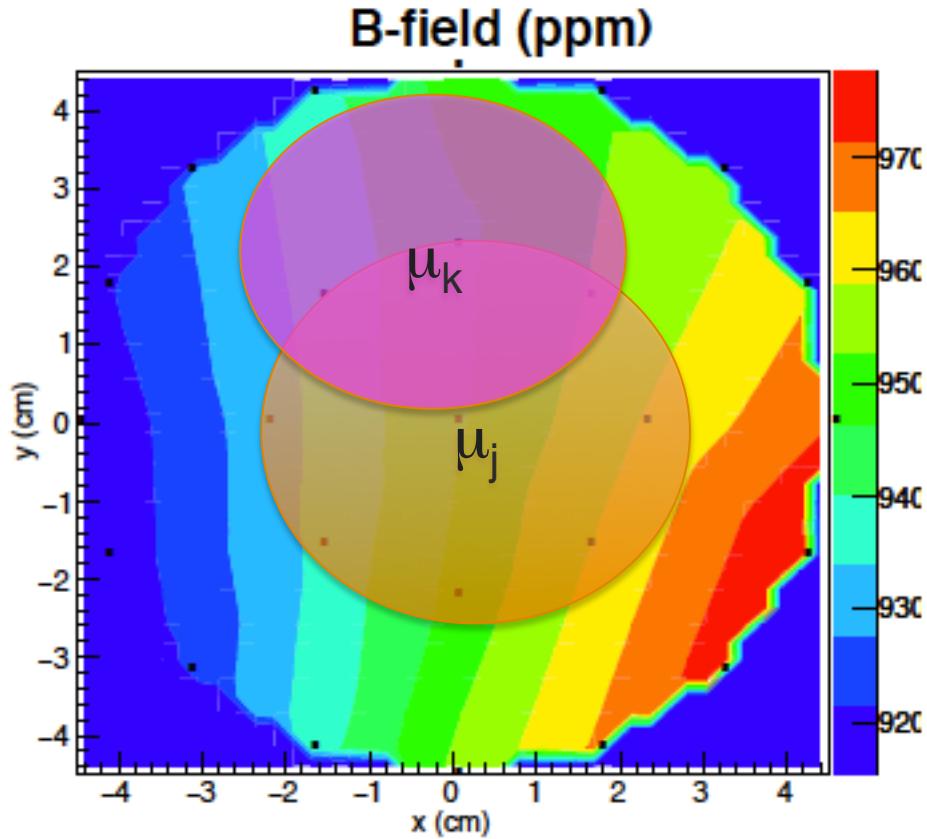
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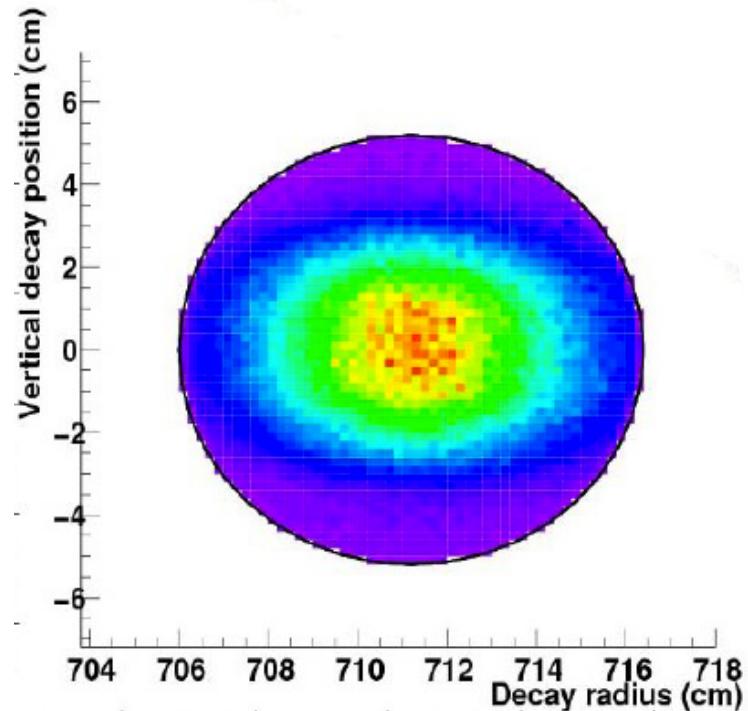
$$a_\mu = \frac{\omega_a / \omega_p}{\mu_\mu / \mu_p - \omega_a / \omega_p}$$

Muon distribution

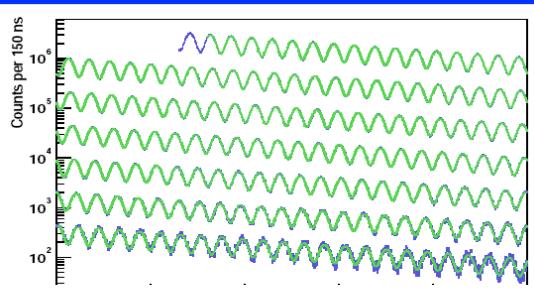


Arbitrary field distribution

- B-field not perfectly uniform
- Must properly weight the field based on the muon distribution

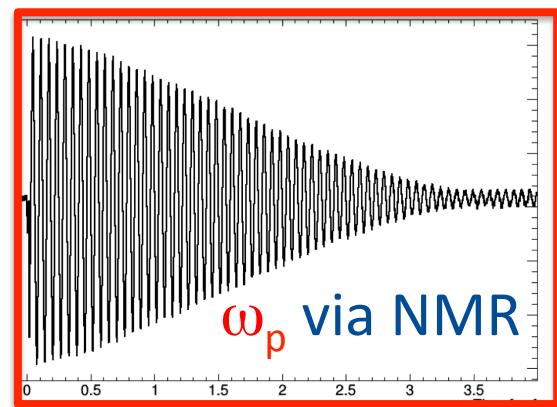


Muon g-2 Measurements



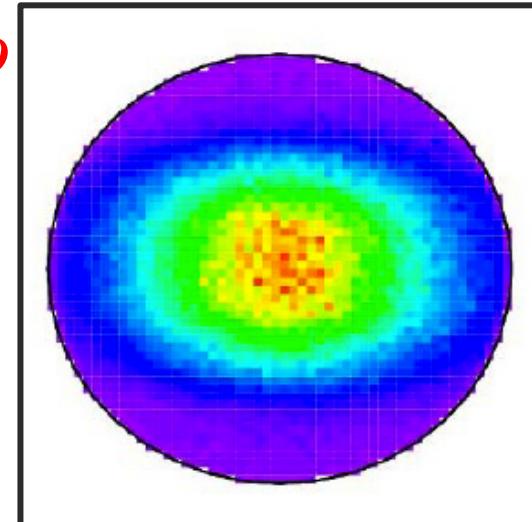
$$\omega_a = \frac{eB}{m} a_\mu$$

Measure B → via NMR →
recast a_μ in terms of proton
precession frequency, ω_p



$$a_\mu = \frac{\omega_a / \omega_p}{\mu_\mu / \mu_p - \omega_a / \omega_p}$$

Externally measured in muonium
hyperfine experiment
25 ppb contribution to muon g-2





EXPERIMENTAL PROGRESS AND DETAILS

E989 Collaboration: 35 Institutes; 155 Members



Domestic Universities

- Boston
- Cornell
- Illinois
- James Madison
- Kentucky
- Massachusetts
- Michigan
- Michigan State
- Mississippi
- Northern Illinois University
- Northwestern
- Regis
- Virginia
- Washington
- Yale
- York College

National Labs

- Argonne
- Brookhaven
- Fermilab



Italy

- Frascati,
- Roma 2,
- Udine
- Pisa
- Naples
- Trieste



China:

- Shanghai



The Netherlands:

- Groningen



Germany:

- Dresden



Russia:

- Dubna
- Novosibirsk



England

University College London

Liverpool

Oxford



Korea

KAIST

The Experimental Approach

Uncertainty Source δa_μ	Status 2015 [ppb]	Projected after E989 [ppb]
Total Theory	420	310
HVP	360	215
HLbL	225	225
Total Exp.	540	140
Stat	460	100
ω_a	180	70
ω_p	170	70

- Previous effort statistically limited → x21 more muons
 - ❖ Facility Upgrades
 - ❖ Improved Muon Storage

Muon Beam Preparation for 21x BNL statistics



- Efficiency
 - Improved pion collection
 - Long decay channel to produce muons
- Delivery Ring to get rid of protons
 - Eliminate background early
 - Start fits earlier
- Fermilab structure
 - 12 Hz rep rate (3 batches)
- ~10,000 muons per pulse successfully injected
- Run Time: 18-24 months

Preparing Existing Tunnels, Building new ones,

5/8/14 start of decommissioning



3/23/15



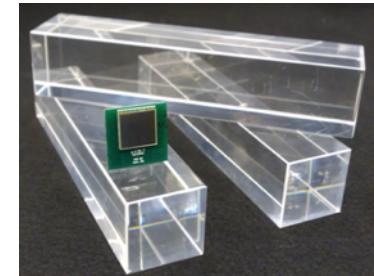
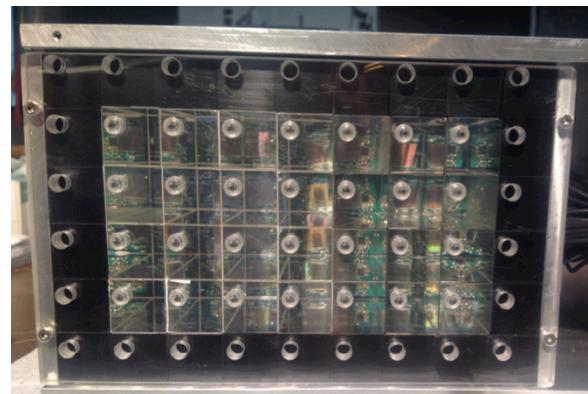
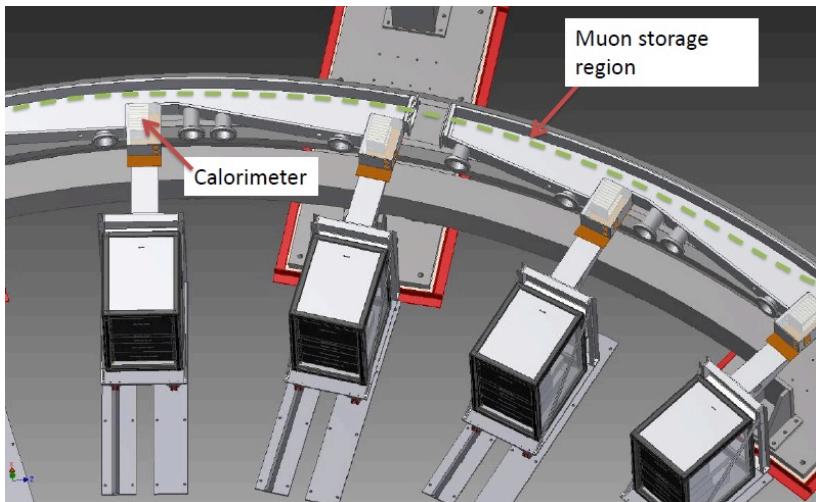
Modest improvements to the muon precession systematics

Uncertainty Source δa_μ	Status 2015 [ppb]	Projected after E989 [ppb]
Total Theory	420	310
HVP	360	215
HLbL	225	225
Total Exp.	540	140
Stat	460	100
ω_a	180	70
ω_p	170	70

- Calorimeter
 - Resolve multiple particles
 - Gain stability
- Tracker
 - Improved positron tracking
 - Informs muon beam dynamics

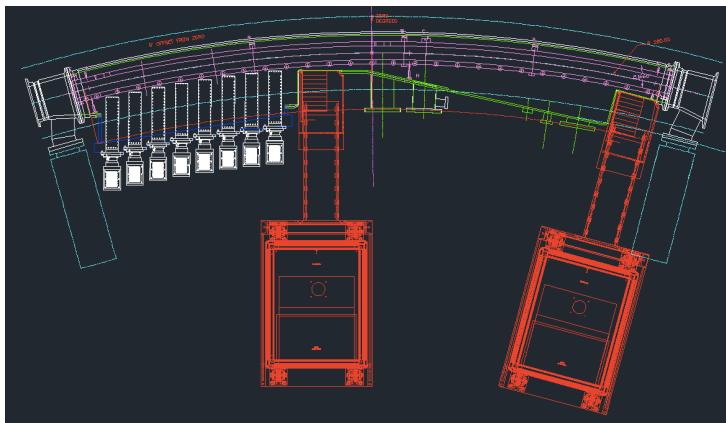
Muon precession

ω_a Instrumentation Upgrades

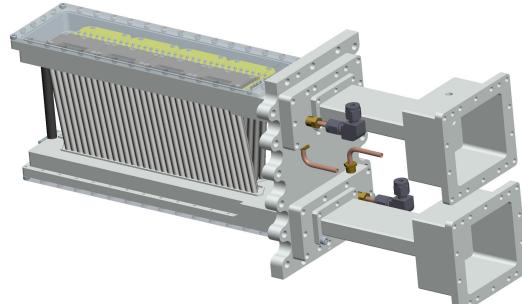


Segmented
compact PbF₂
Cherenkov

~3 cm and ns spatial/temporal separation



Thin straws



Precision positron tracking



Modest improvements to the proton precession systematics

Uncertainty Source δa_μ	Status 2015 [ppb]	Projected after E989 [ppb]
Total Theory	420	310
HVP	360	215
HLbL	225	225
Total Exp.	540	140
Stat	460	100
ω_a	180	70
ω_p	170	70

- New set of NMR probes
- Generate a more uniform field

Proton precession

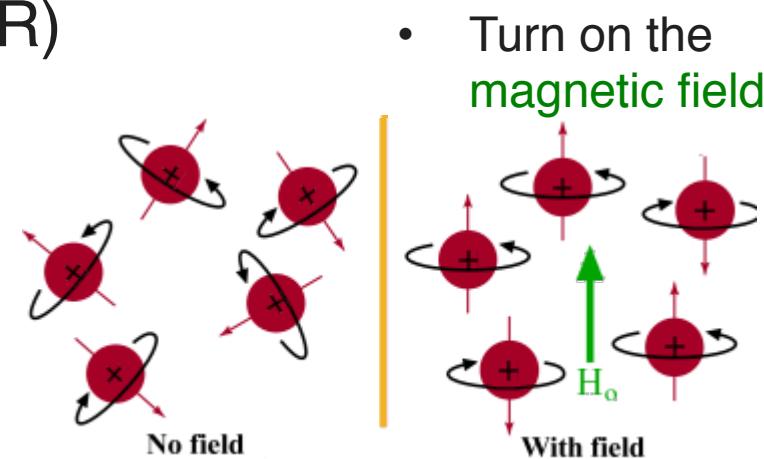
Proton Precession Frequency: How We Measure

- Nuclear Magnetic Resonance (NMR)
 - Extremely Precise (~ 10 ppb)
 - Measures Total Field

RF Coils tip proton

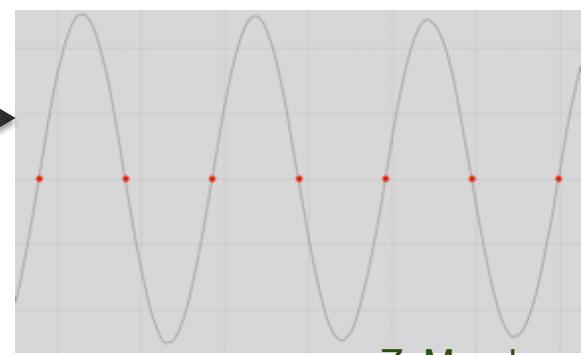
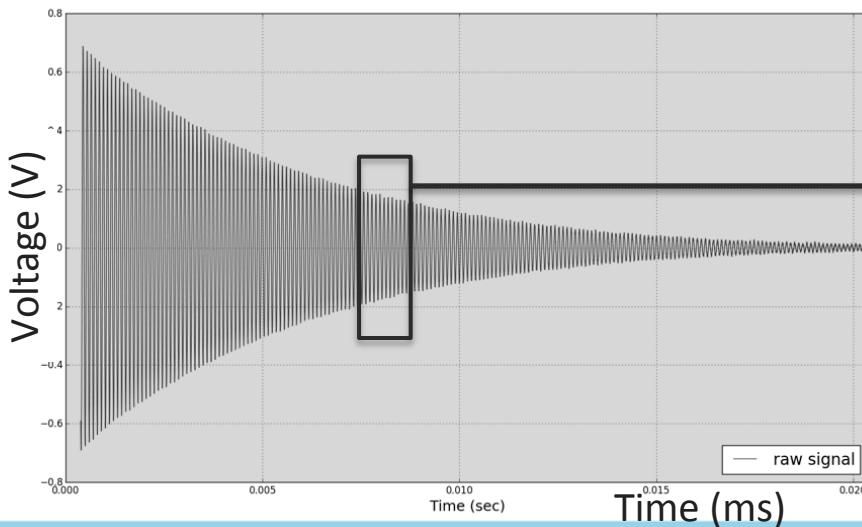
Magnetization by $\pi/2$

Precessing protons induce
EMF in **same coils**



Digitize to extract ω_p

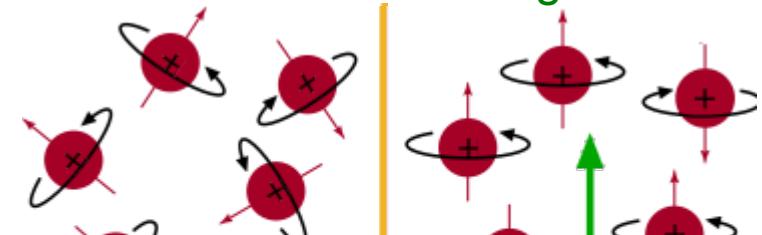
Count zero crossings



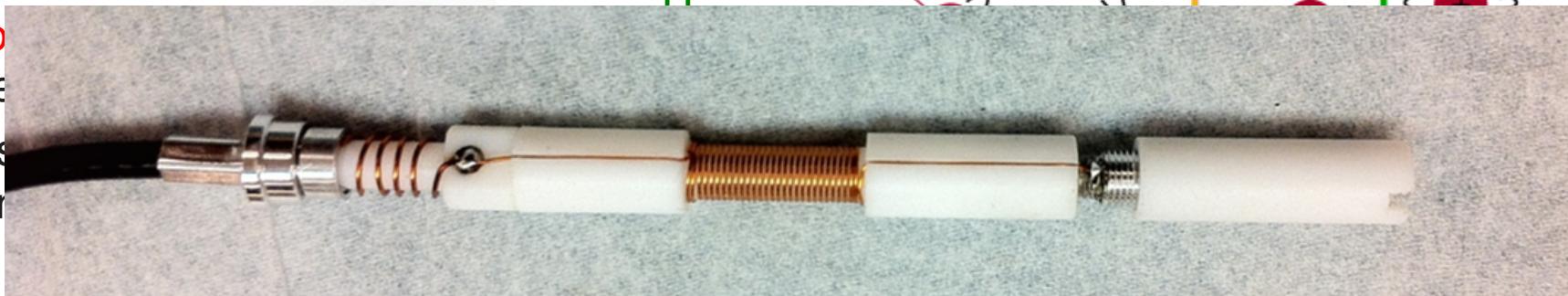
Proton Precession Frequency: How We Measure

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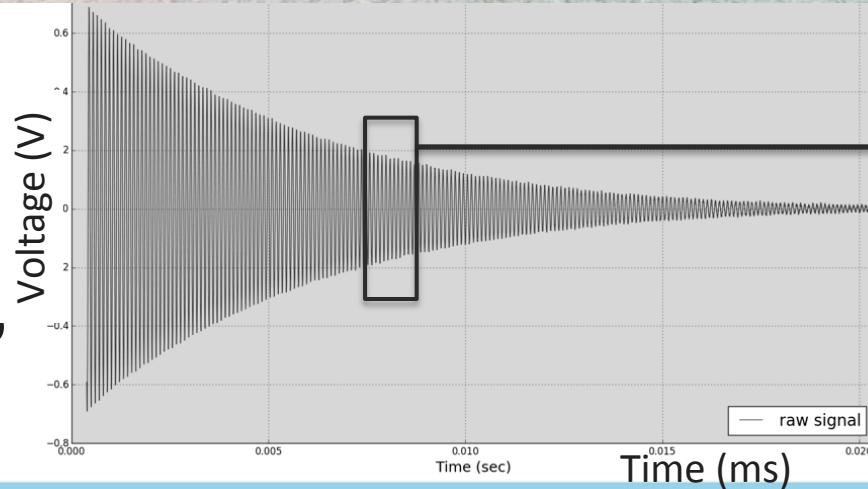
Use a proton-rich sample



RF Co
Magne
Preces
EMF in



Digitize to extract ω_p



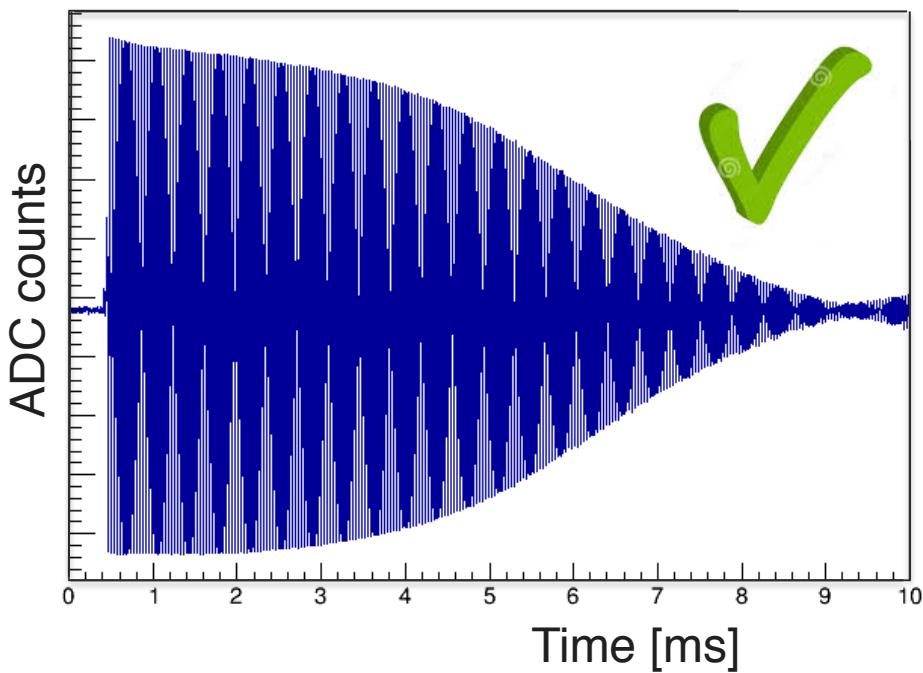
Count zero crossings



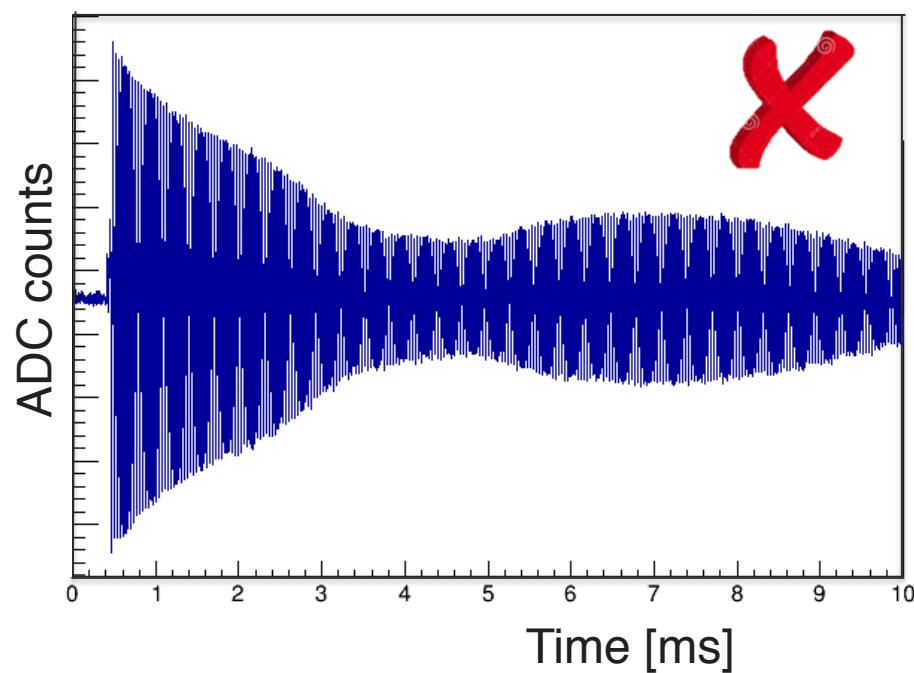
Z. Meadows

Signal Shape informs us about gradients

Small Field Gradients



Large Field Gradients



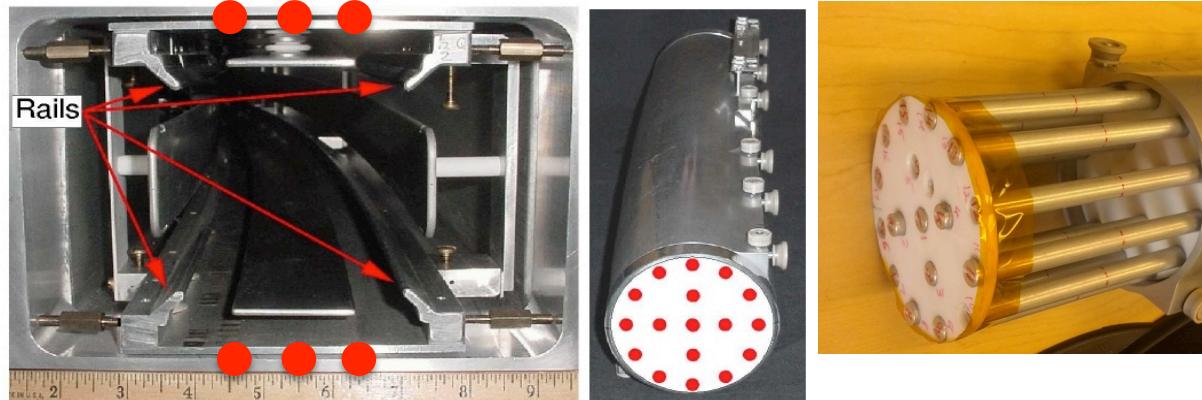
Signal degrades more quickly in high gradients

Proton Precession Frequency: Why We Measure

- Driving Goal: Extract Magnetic Field experienced by the Muons

- Extracting ω_p

1. Measure the field when the muon beam is OFF



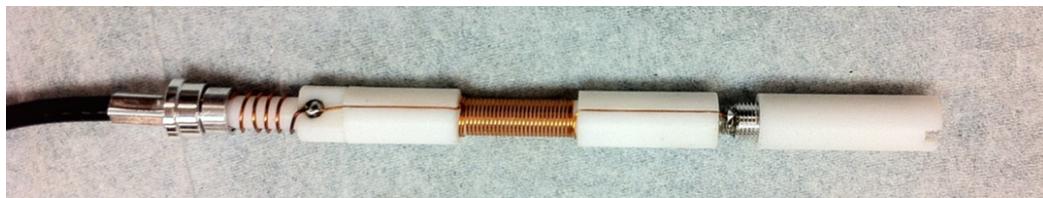
2. Monitor the field when the muon beam is ON

3. Calibrate the absolute frequency of our probes with a reference probe

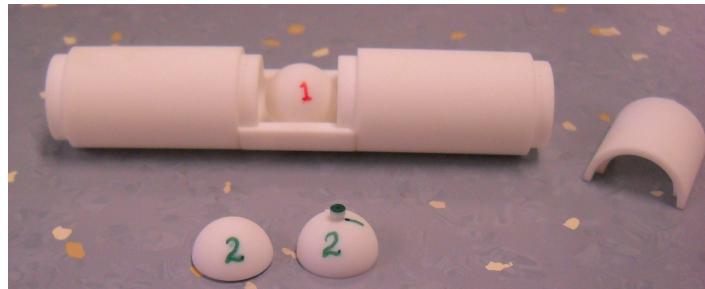
$$\omega_L(\text{probe}) = (1 - \delta)\omega_L(\text{free})$$



ω_p Instrumentation Upgrades



400 New Tunable NMR Probes



Absolute Calibration Probes



Low-noise electronics



68-cm bore MRI magnet w/ high stability

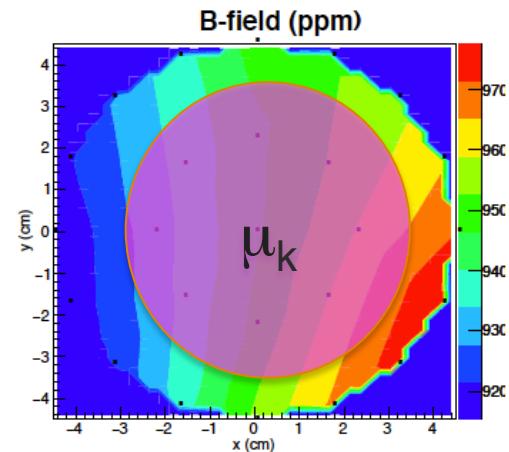


We need to prepare a highly uniform magnetic field

- Driving Goal: Extract Magnetic Field experienced by the Muons
- Practical Constraints

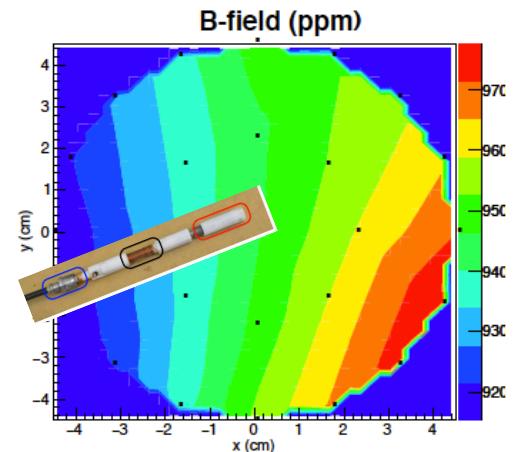
Muon beam not “perfect”

- Non-zero momentum spread
- Spatial extent → muons will sample the storage region



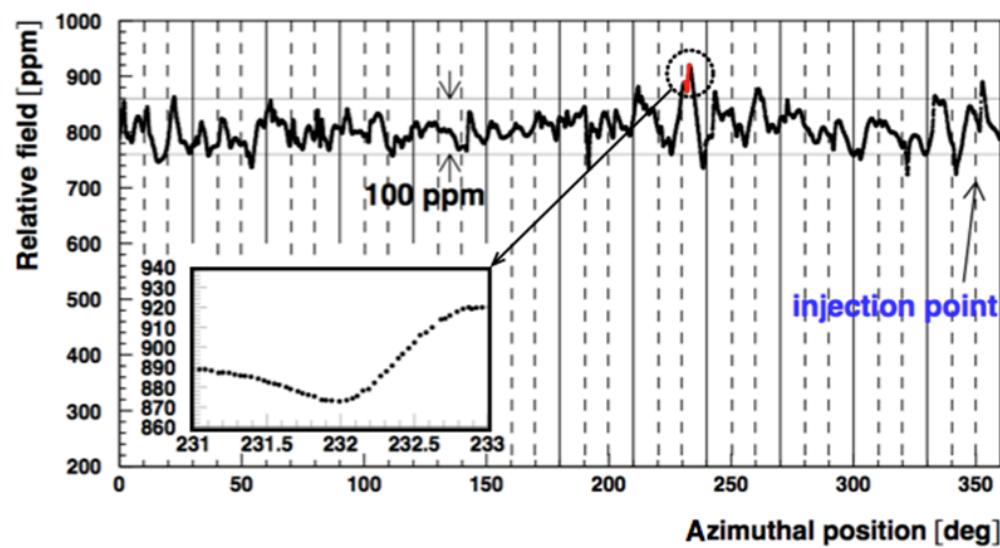
Probes have finite size

- Placement reproducibility → may sample slightly different fields when trying to measure $B(r, \theta, z)$



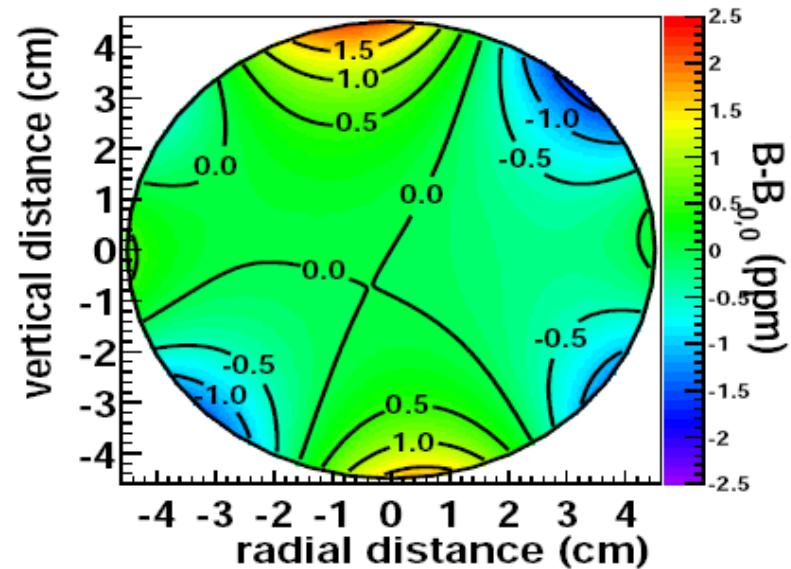
Extract the field the muons experience

Field vs. Azimuth



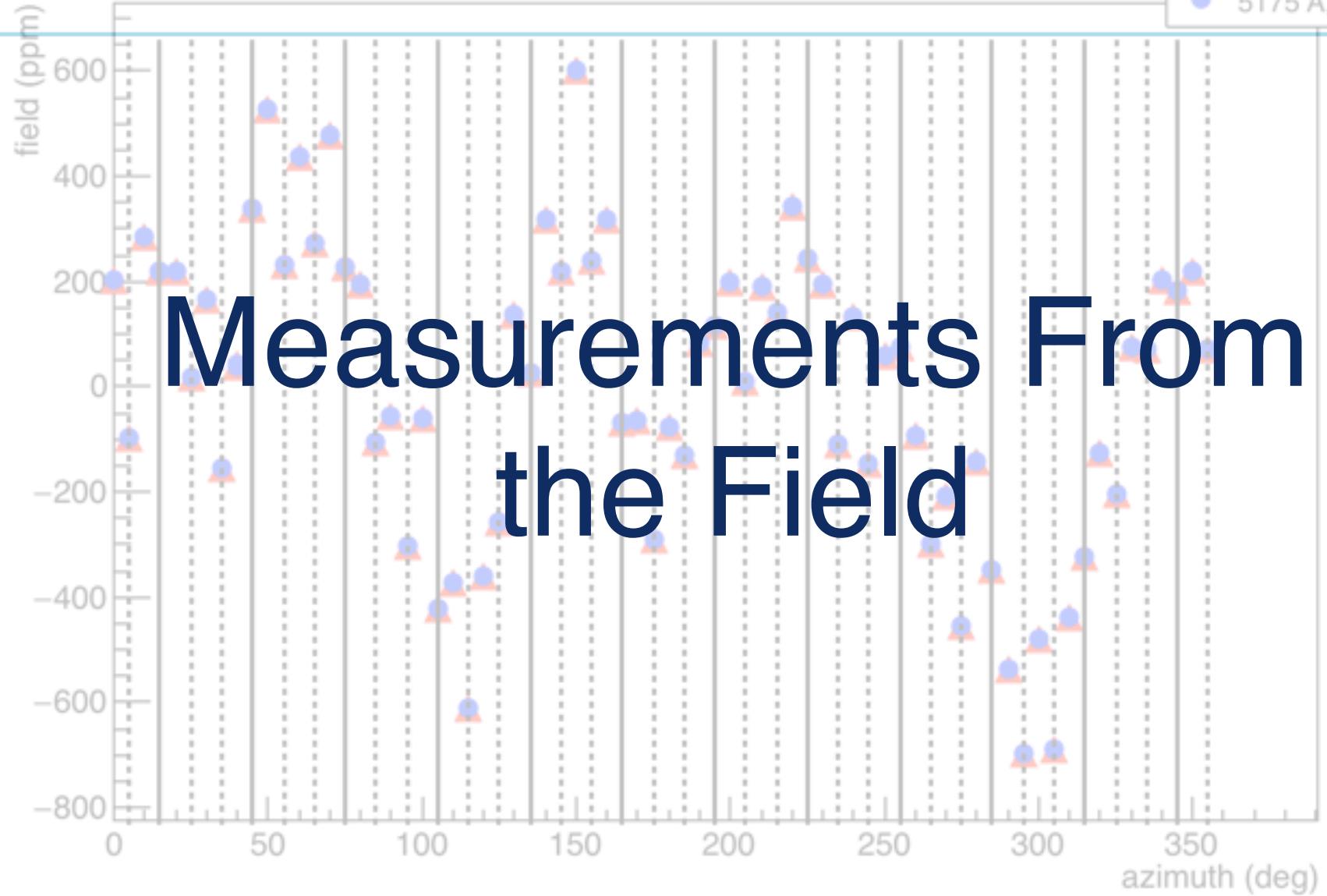
Goal: +/- 25 ppm

Azimuthally Averaged
Field vs r,z

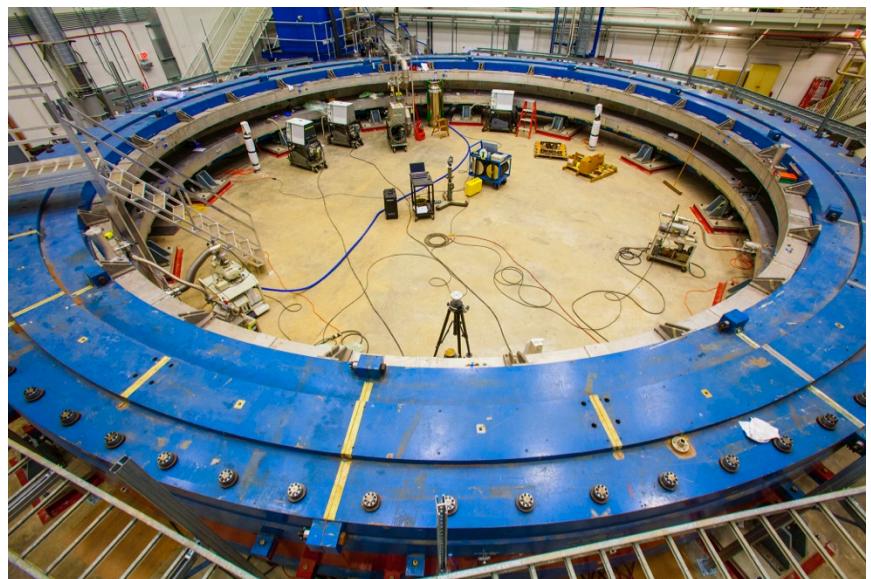
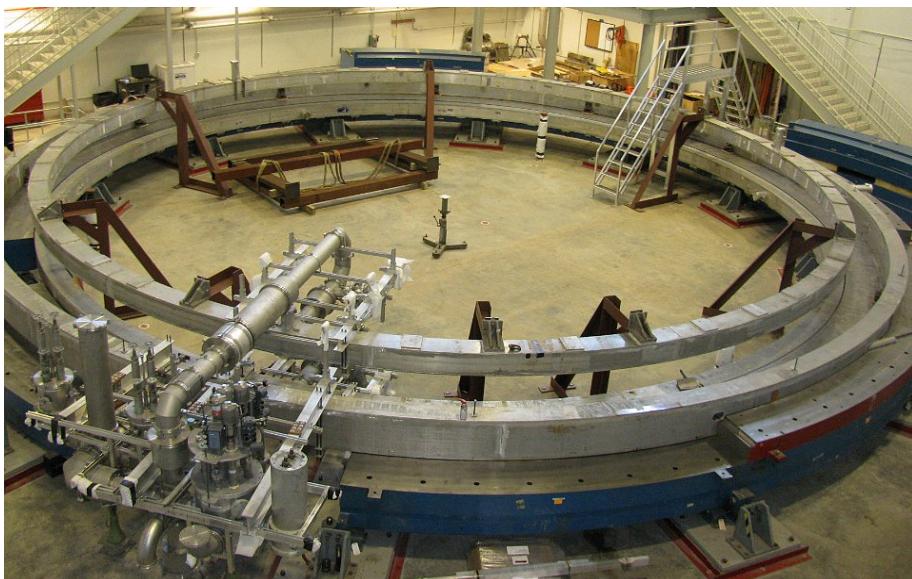
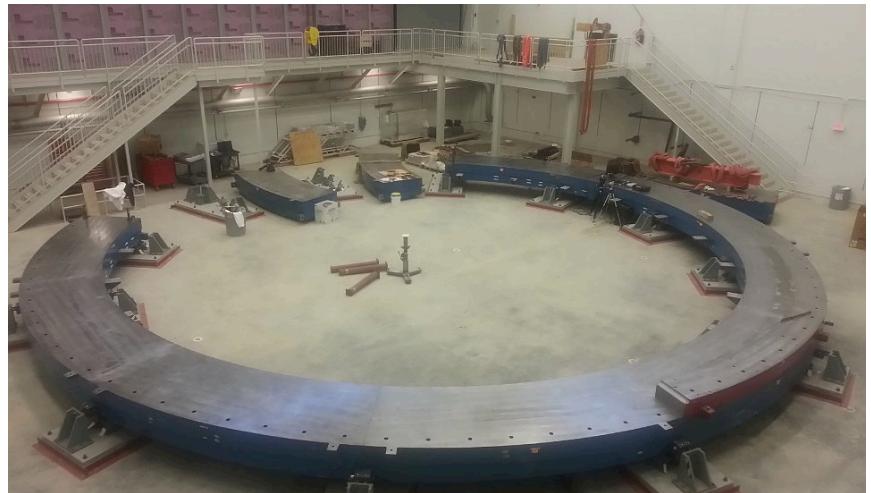


Bennett et al. 10.1103/PhysRevD.73.072003

Goal: +/- 0.5 ppm



Ring Reconstruction (July 2014-June 2015)

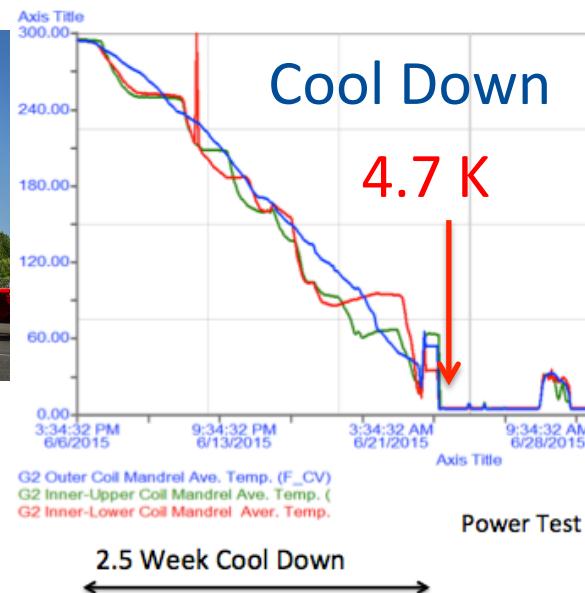


Cooled Down, Powered up

Summer 2013

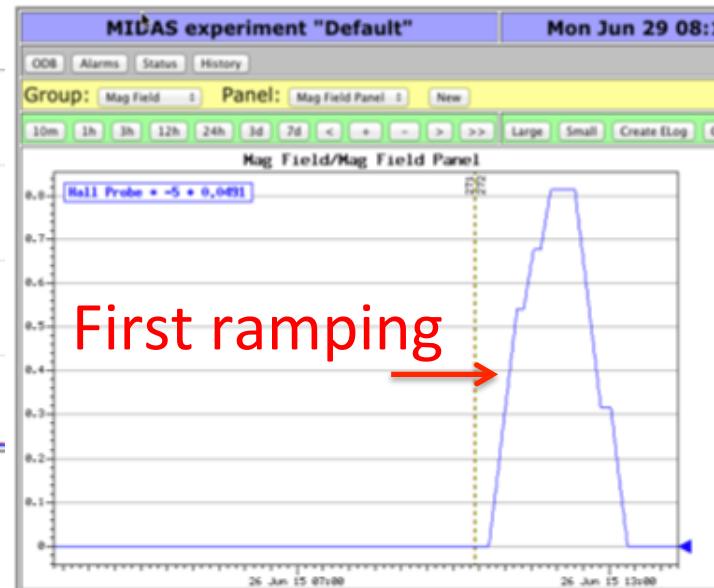


Summer 2015



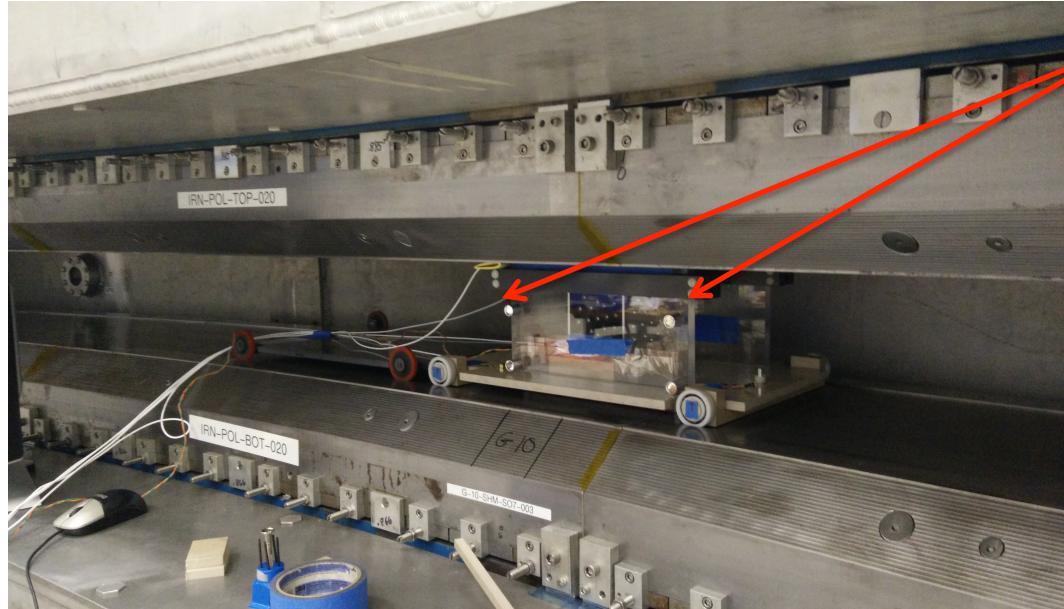
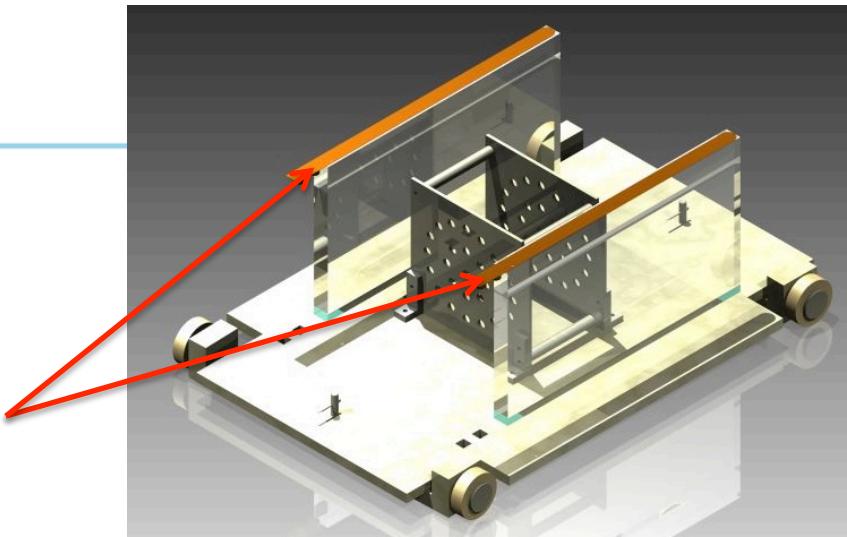
Full power, full field on Sep 21, 2015

Online display B-Field



Shimming Cart

- Multipurpose instrument
 - 25 **NMR Probes** for field
 - 4 **capacitive gap sensors**
 - Measure pole alignment
 - 70 nm resolution
 - Few micron reproducibility



- 4 Position sensors
 - Corner cube reflectors
 - $\sim 25 \mu\text{m}$ res
 - Cart r, θ, z



Preparing for a scan [~60 degrees]

Shimming Cart



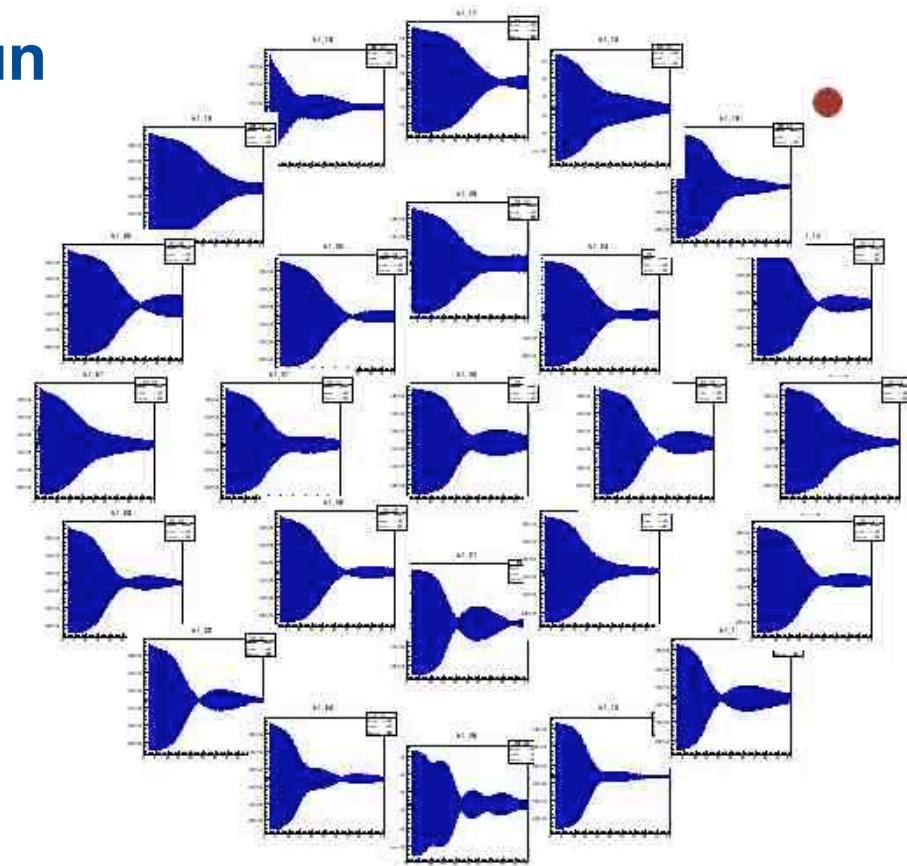
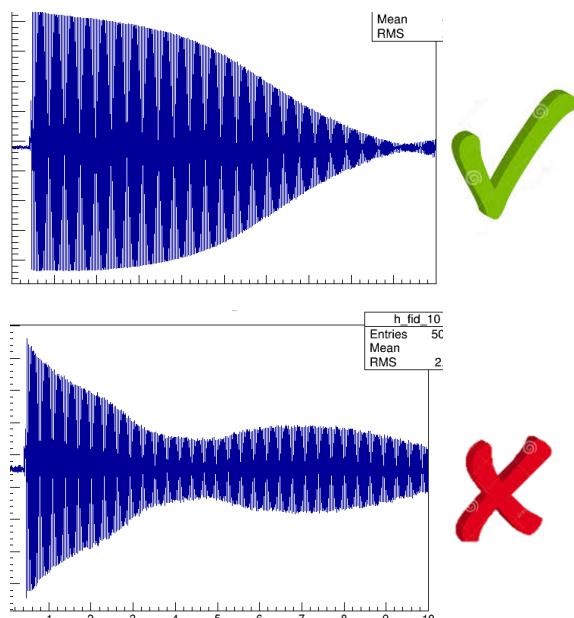
Tether

NMR Multiplexors,
Electronics Table

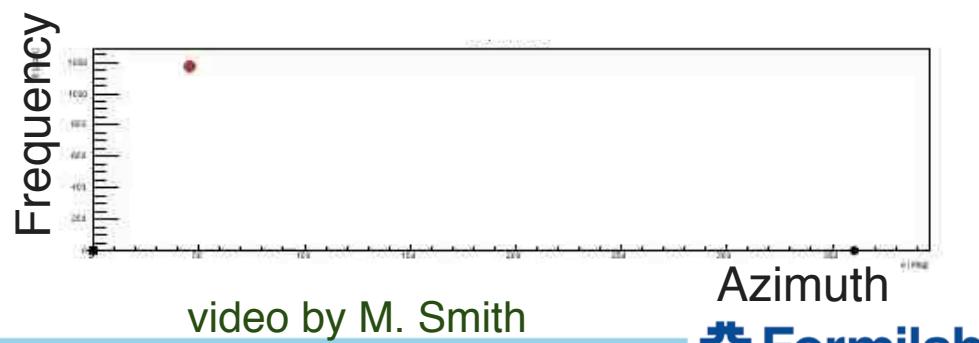
Laser DAQ

Laser Tracker

Field from a representative run



- Red Point → Azimuthal ring position
- Black Curve → Extracted frequency from center probe

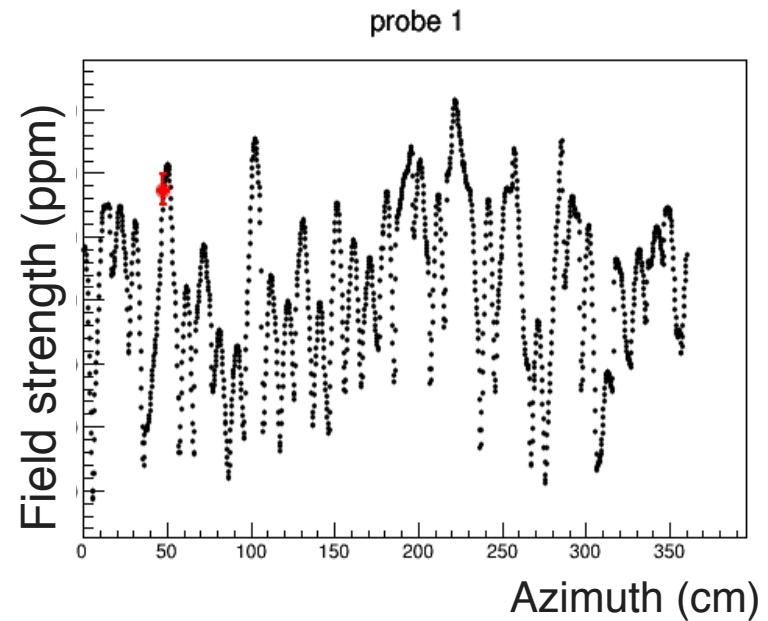
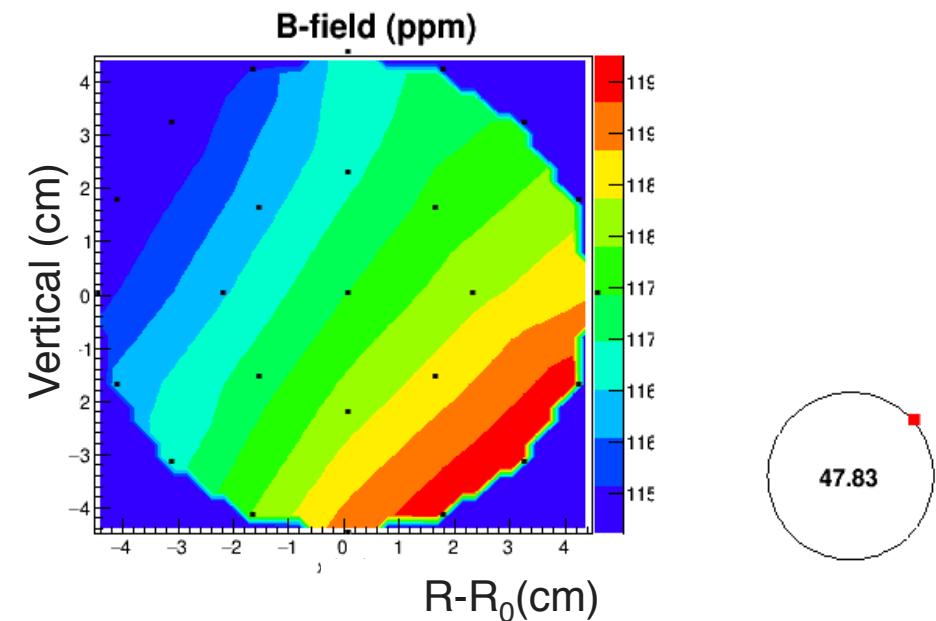


video by M. Smith

Azimuth
Fermilab

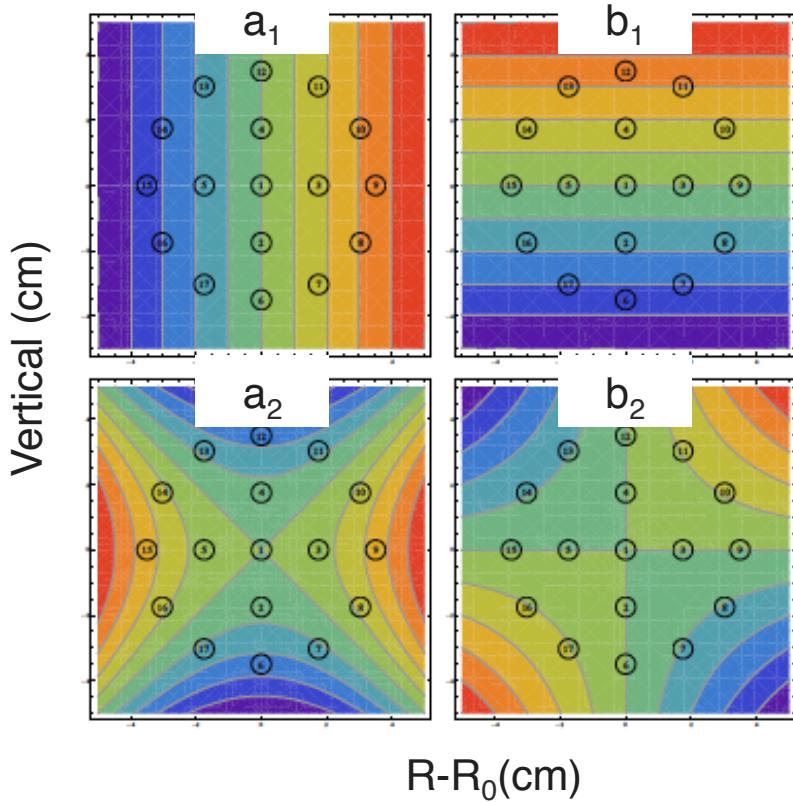
Field from a representative run

- Black Points → Measurements with NMR Matrix
- Color → Field Contours
- Red Point
 - Error bar → Relative Field Variation in azimuthal plane



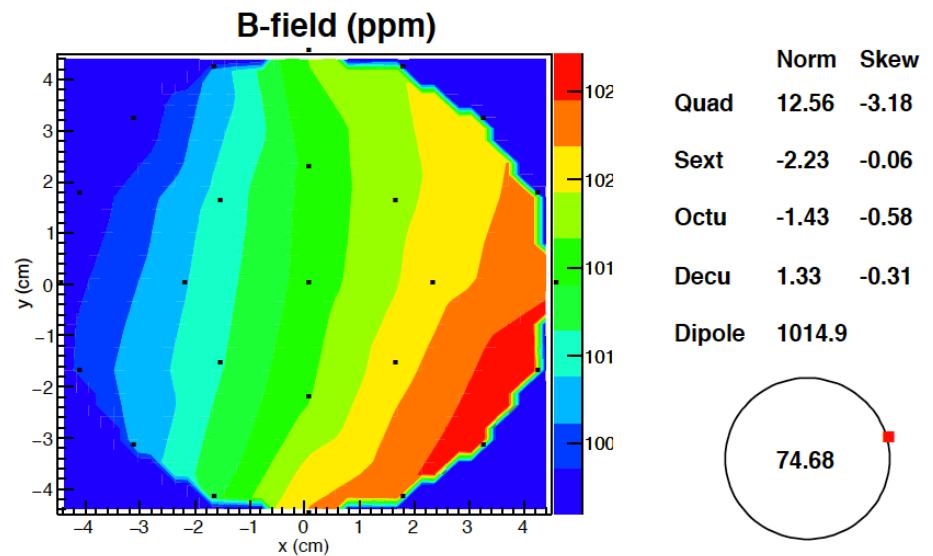
Decompose field into multipole components

- Sample at NMR probe locations
- Fit to sum of i-orders of multipoles



2D approximation for small B_x , B_θ

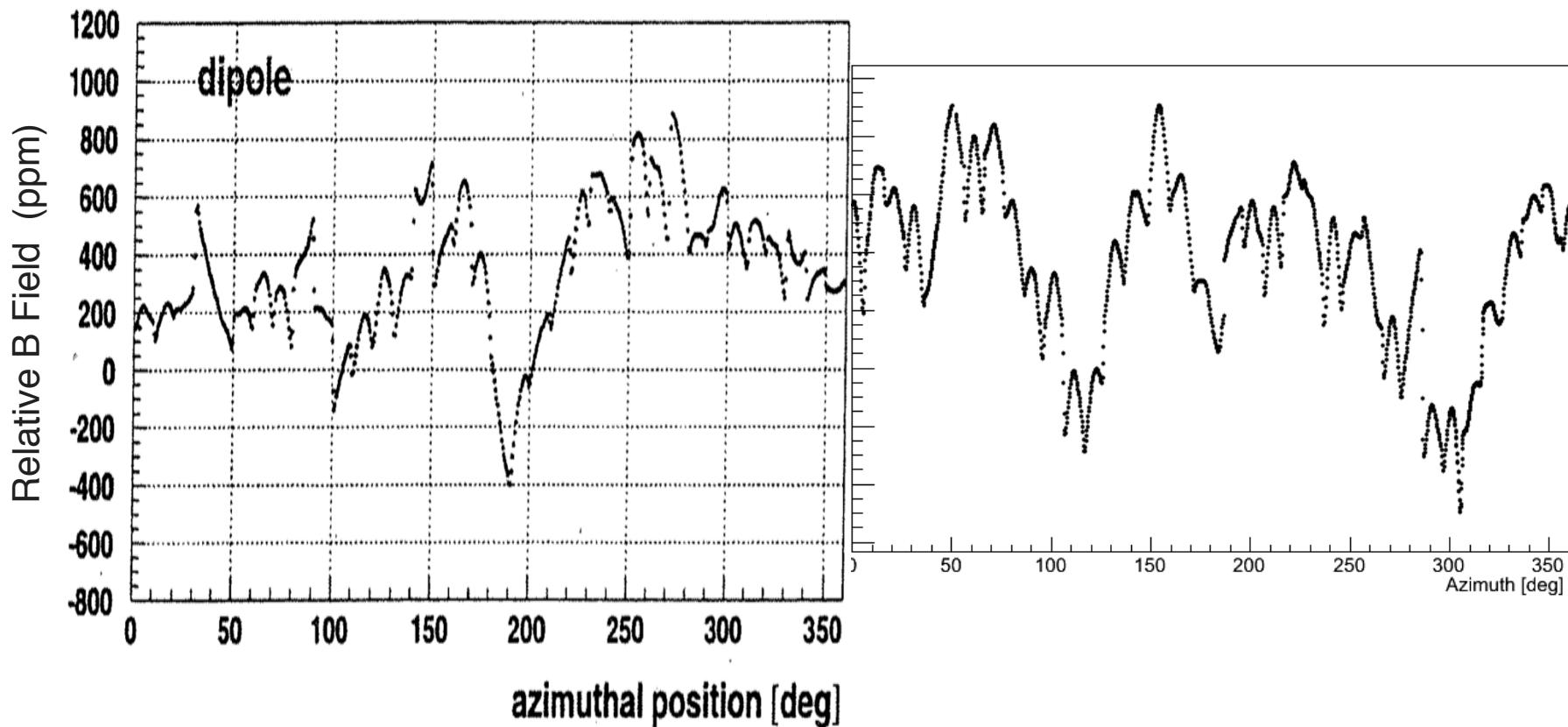
$$B(x, y) = B(r, \theta) = B_0 + \sum_{i=1}^n \left(\frac{r}{r_0} \right)^i [a_i \cos(i\theta) + b_i \sin(i\theta)]$$



First Full Field Azimuthal Scan Results

June 1996

October 14 2015



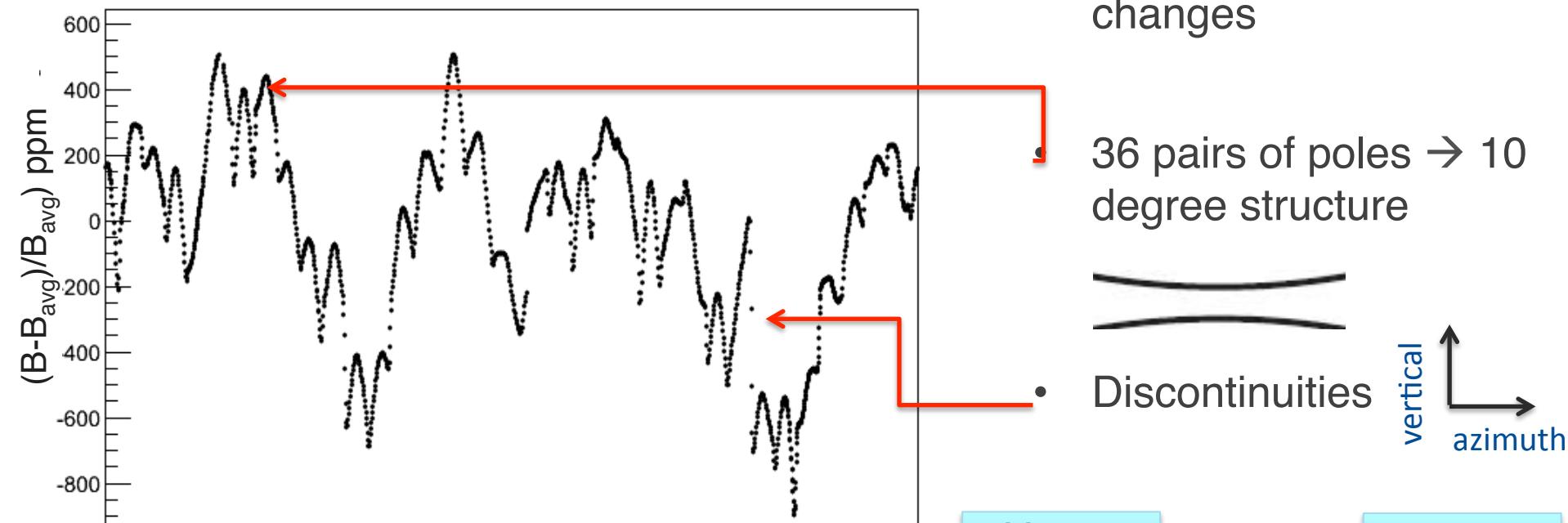
1300 ppm variation



1400 ppm variation

Closer Look at the variations

First Magnetic Field Map, Oct 14 2015



Upper

Poles

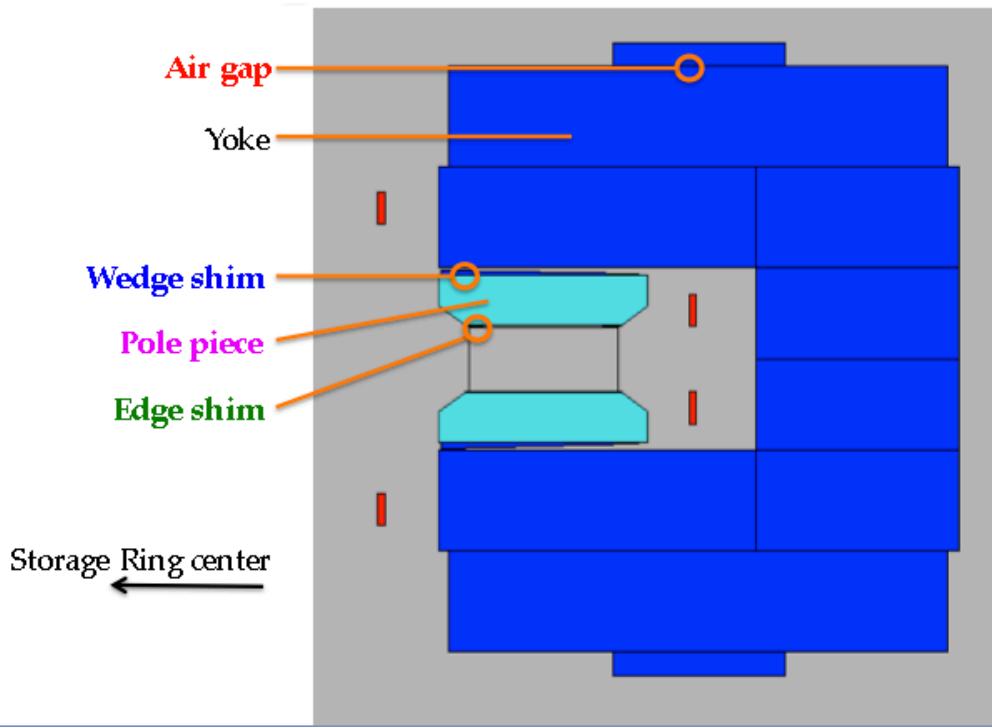
Lower

Poles

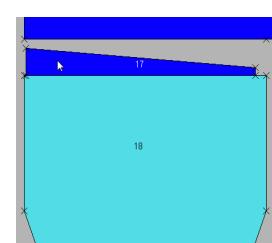


Maximize Field Uniformity: Shim the various multipole components with 1000s of Knobs

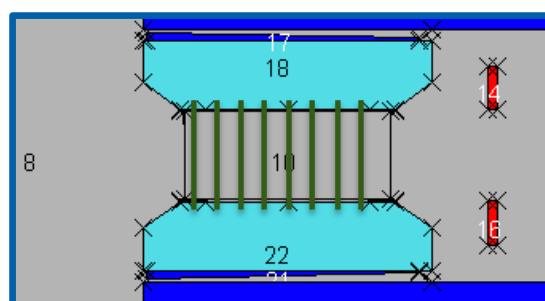
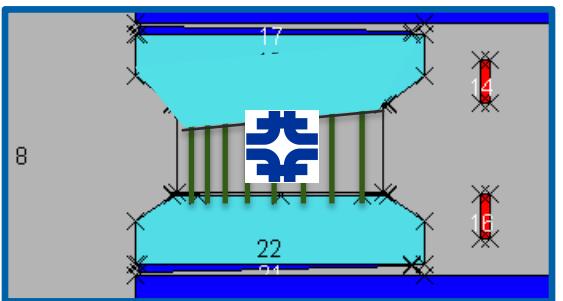
OPERA 2D and 3D simulations



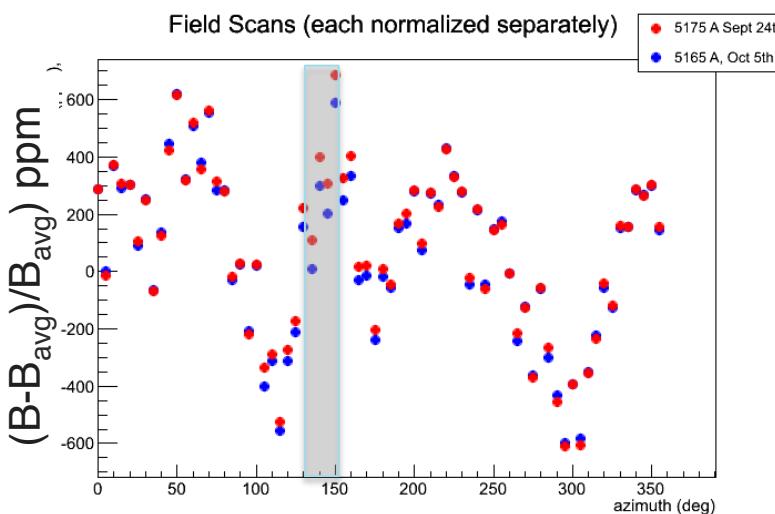
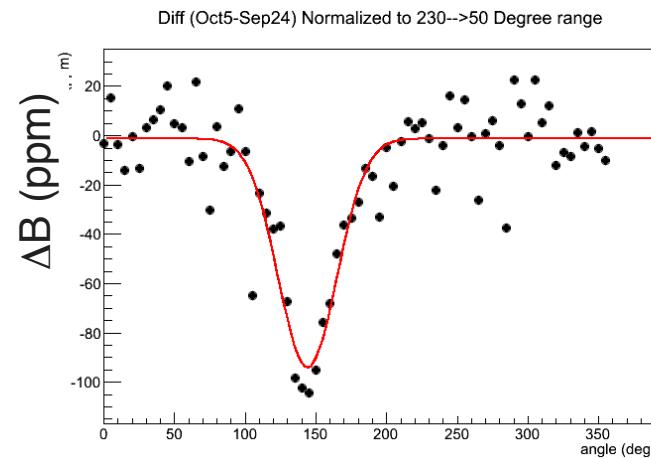
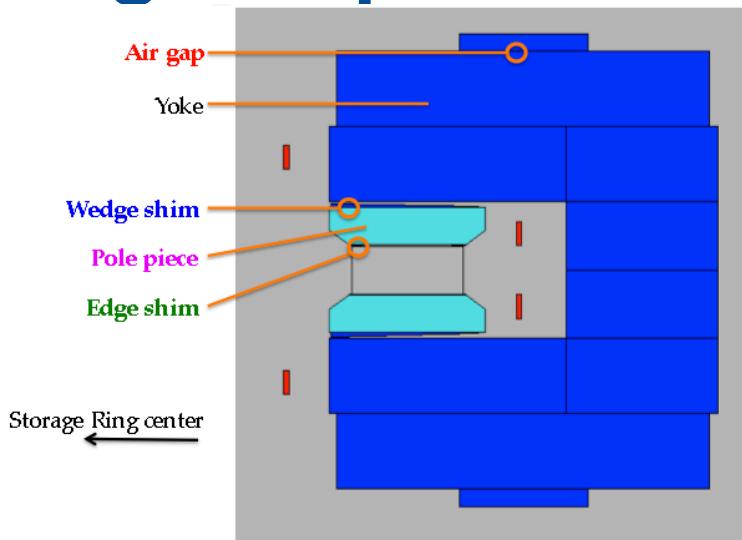
- Dipole Knobs compensate for material non-uniformities, residual pole-pole gap, etc
 - Main Magnet Current
 - 36 Pairs of Poles (gap)
 - 864 wedges in yoke-pole gap
 - 48 “Top-Hat” Steel segments



- Quadrupole Knobs
 - Angle of Wedge Shims
 - 36 Pairs of Poles (tilts)

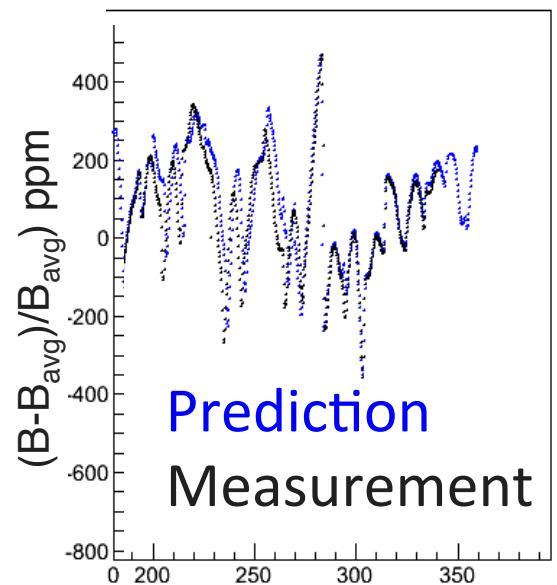


Single Top Hat Knob Calibration



Matches OPERA prediction (<5%)

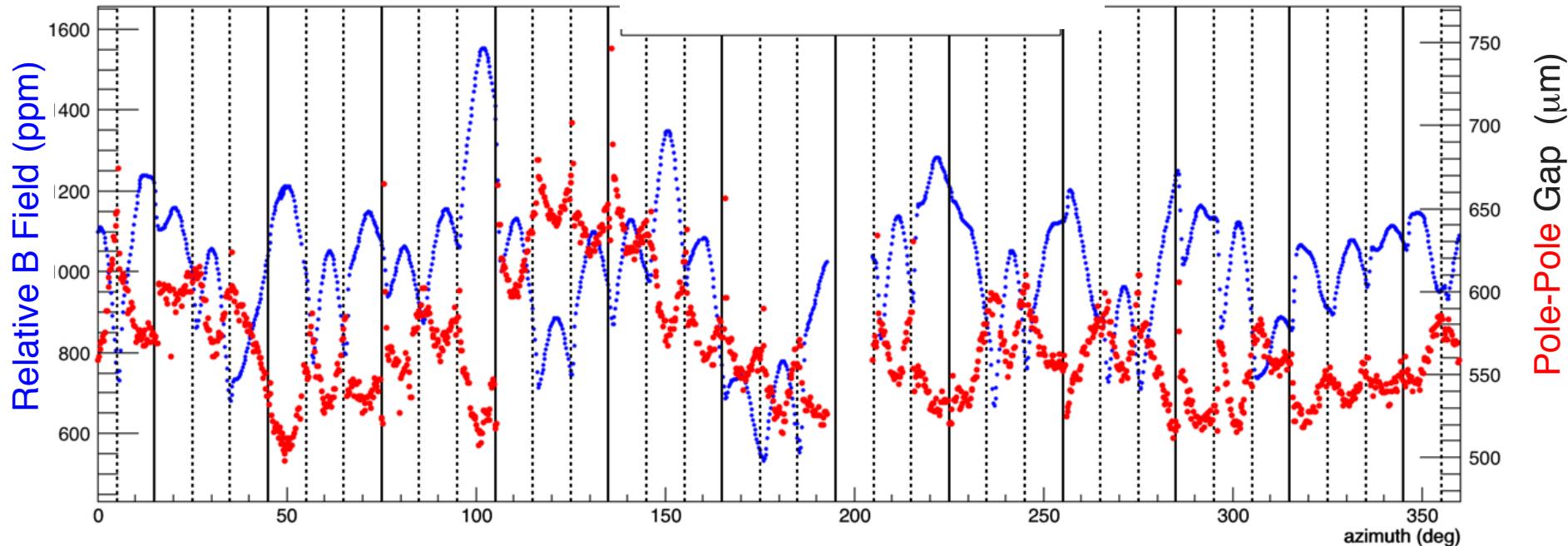
Program of dipole adjustments



Pole Gap Measurements

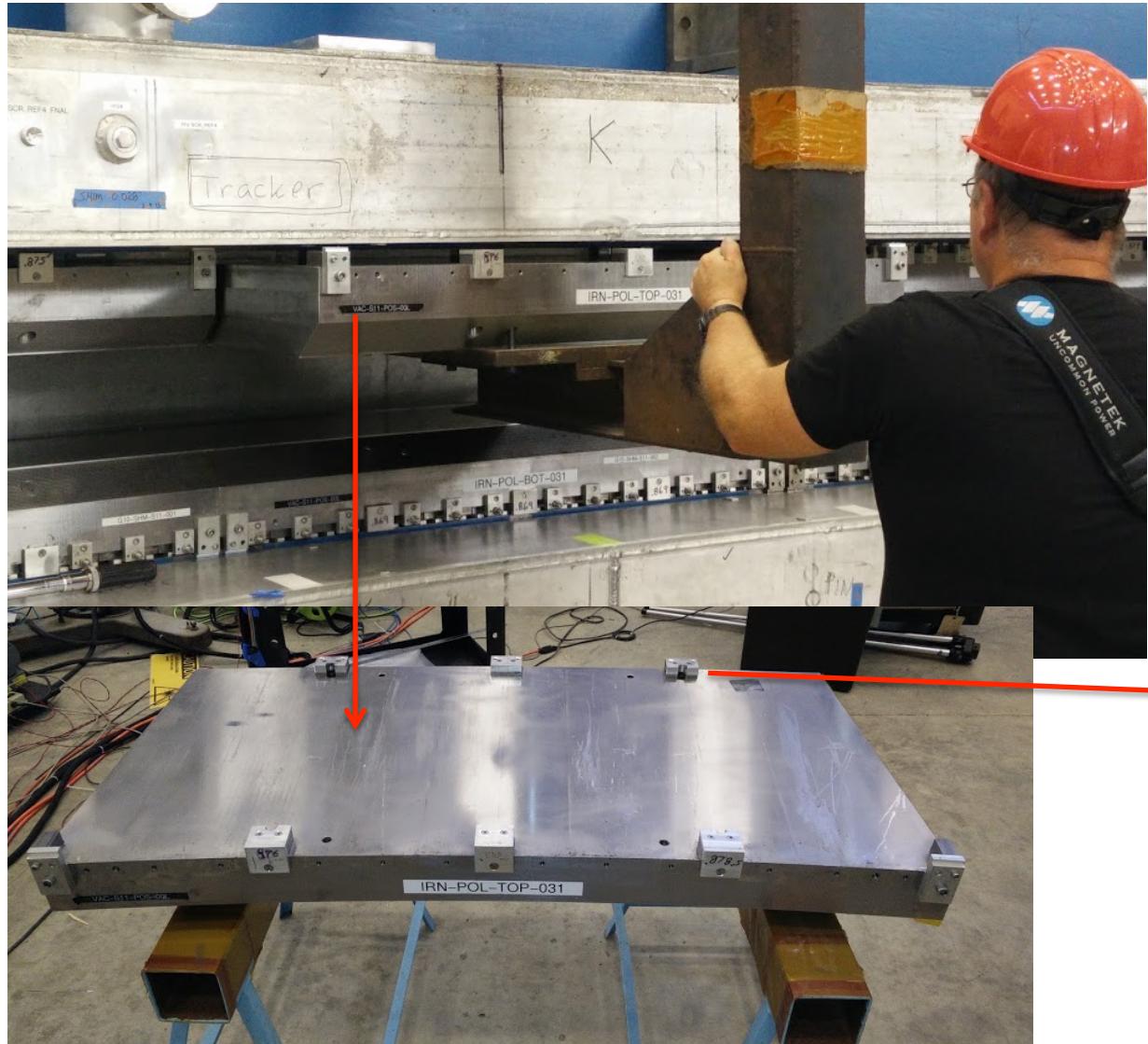
- Vertical lines show pole-pole boundaries

Field, Pole Gap vs azimuth

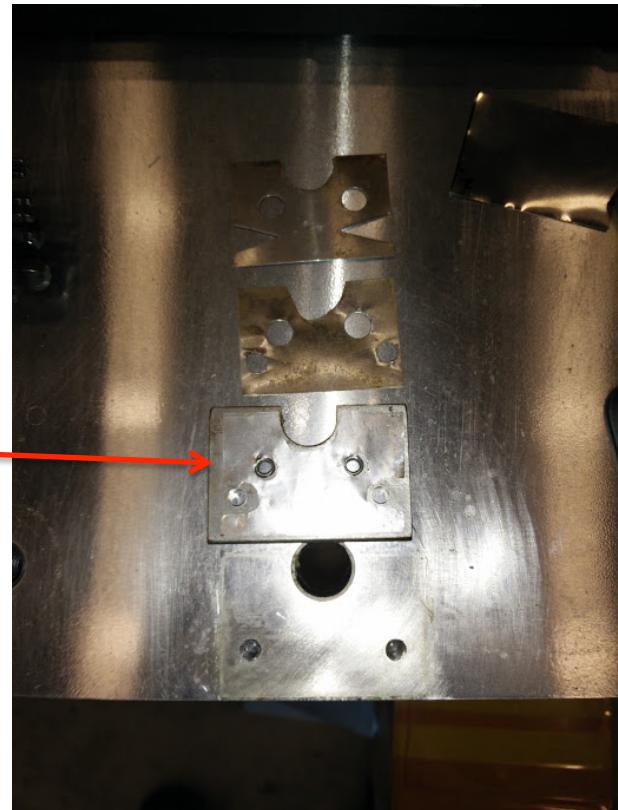


- Alignment is good to ~100 microns,
- Anti-correlation between vertical **pole gap** and **field**

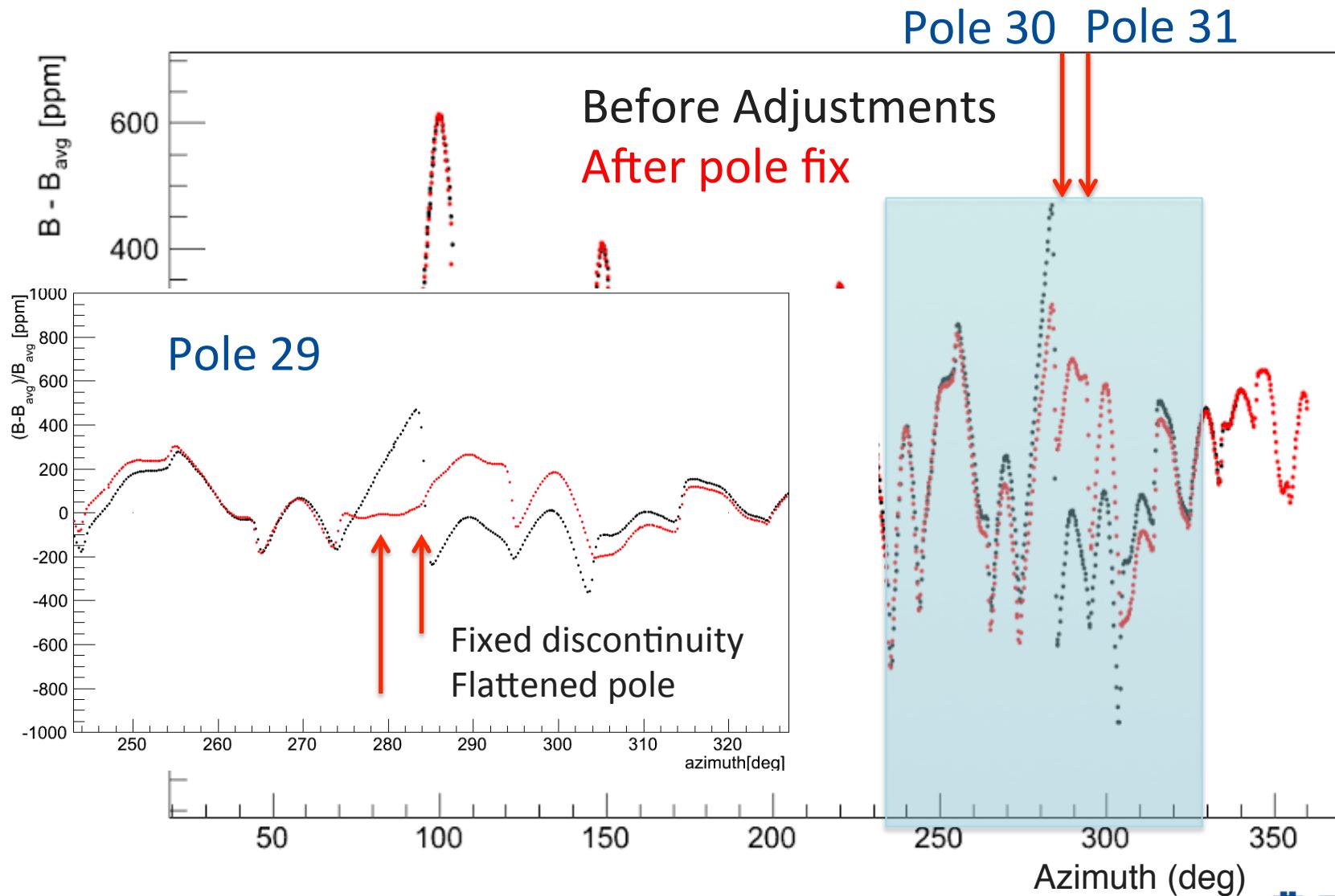
Pole Steps: Align pole surfaces



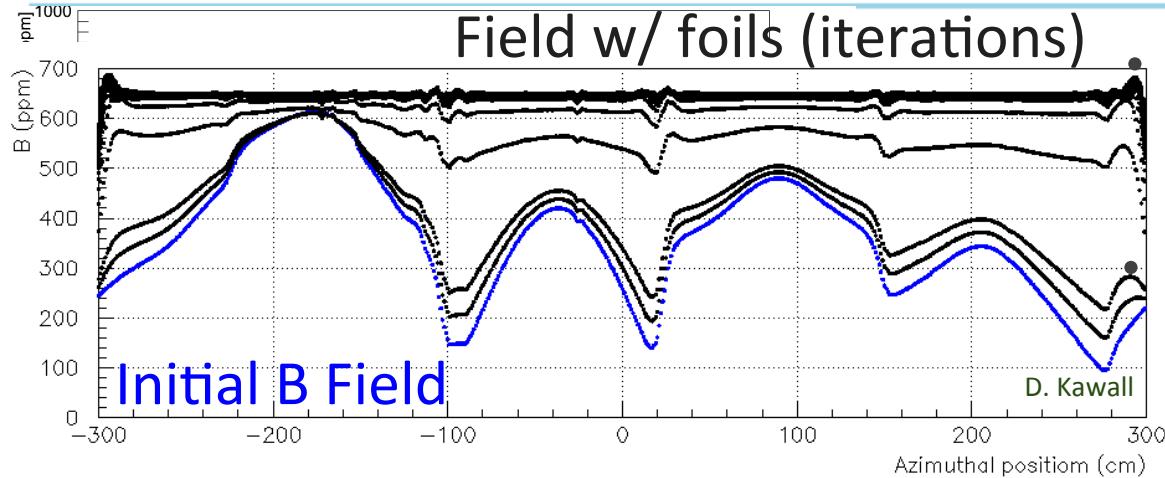
Set Pole gaps: Insert 1 to 10 thin shims ($25 \mu\text{m}$ thick) with spacers



Pole realignment smooths the field

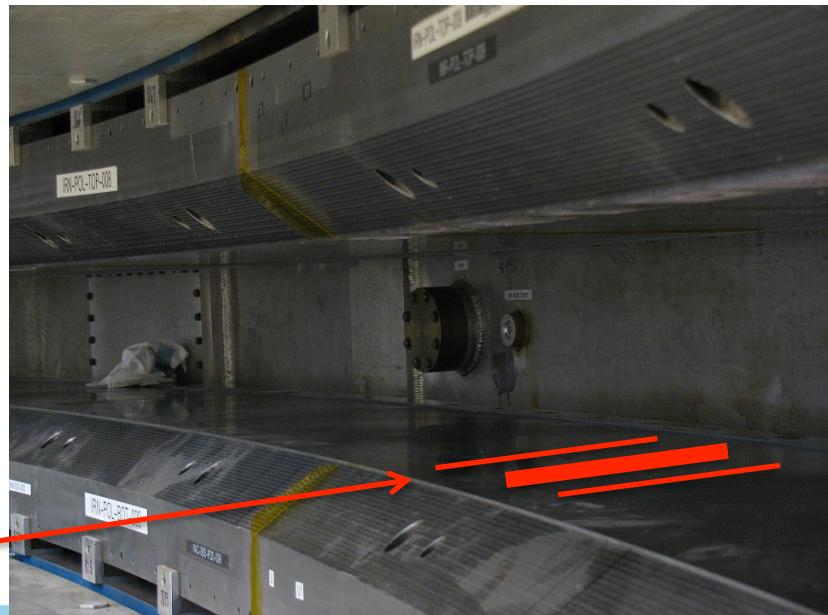
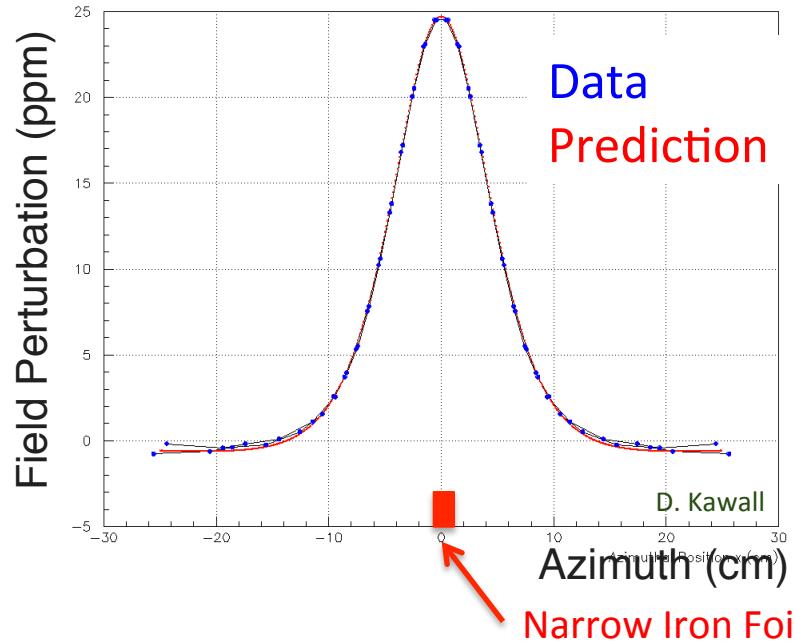


Iron Foil Shimming on the Pole Surface



Treat Low-carbon steel foil as ensemble of magnetic moments

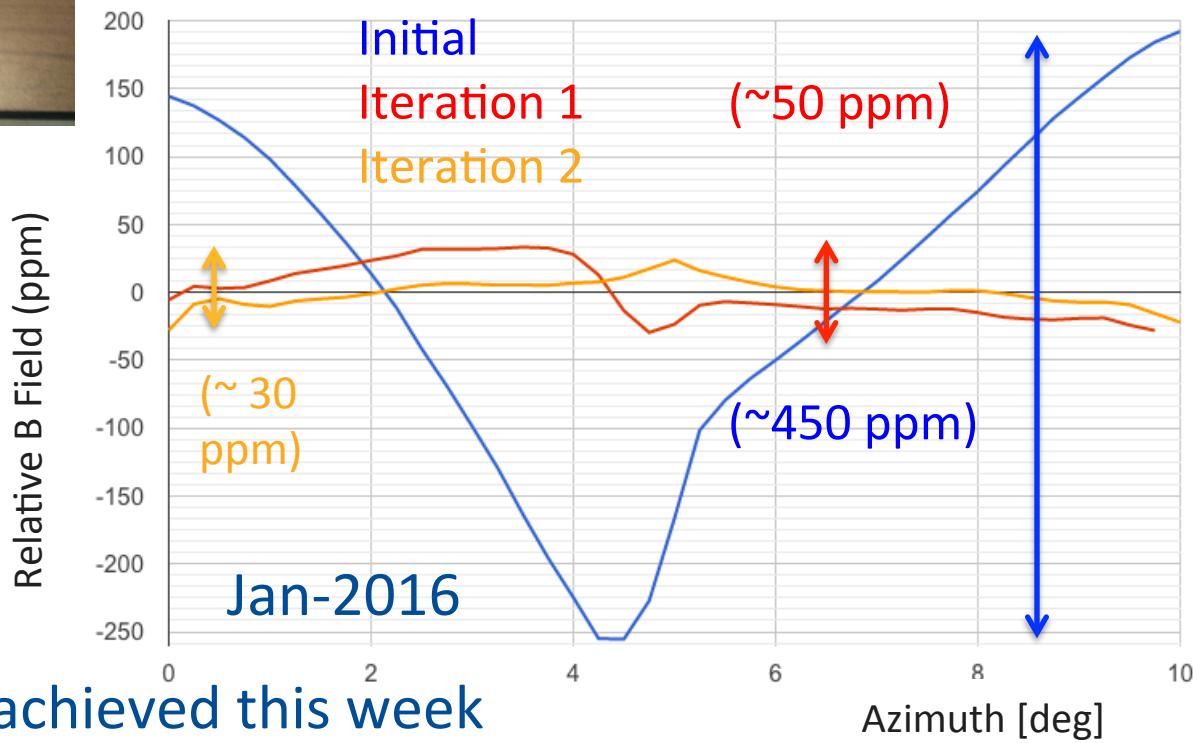
Construct ensemble of foils with different thicknesses



Attacking the largest variation region in the ring...



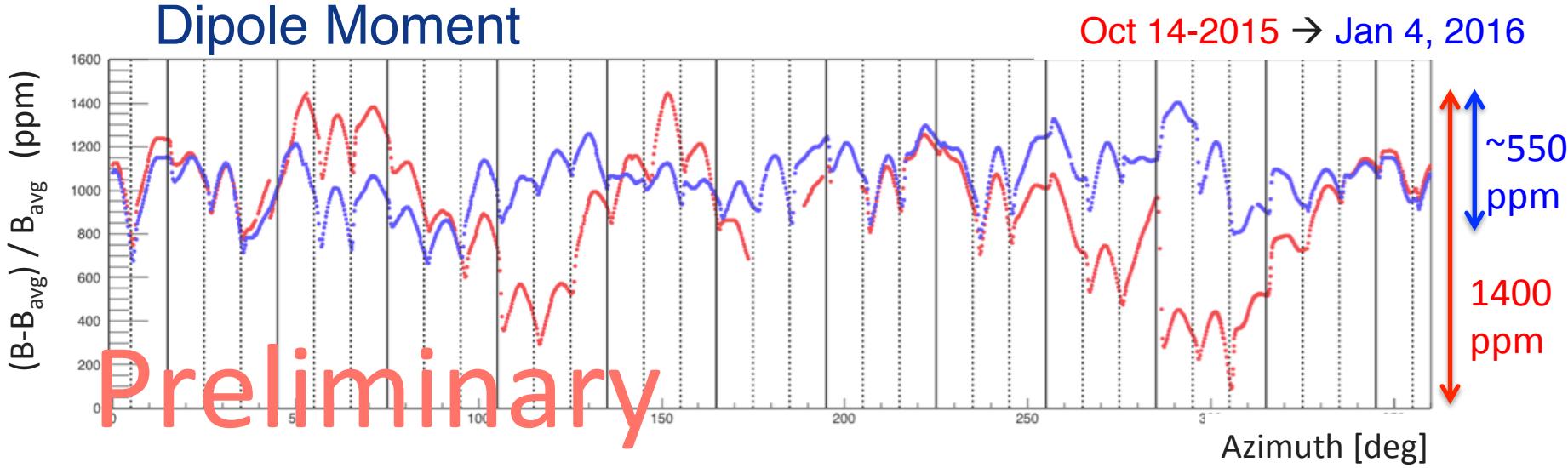
- Constructed grid of Iron Foils
- 1-cm-wide strips, every 2 cm
- Thicknesses from $25 \rightarrow 150 \mu\text{m}$



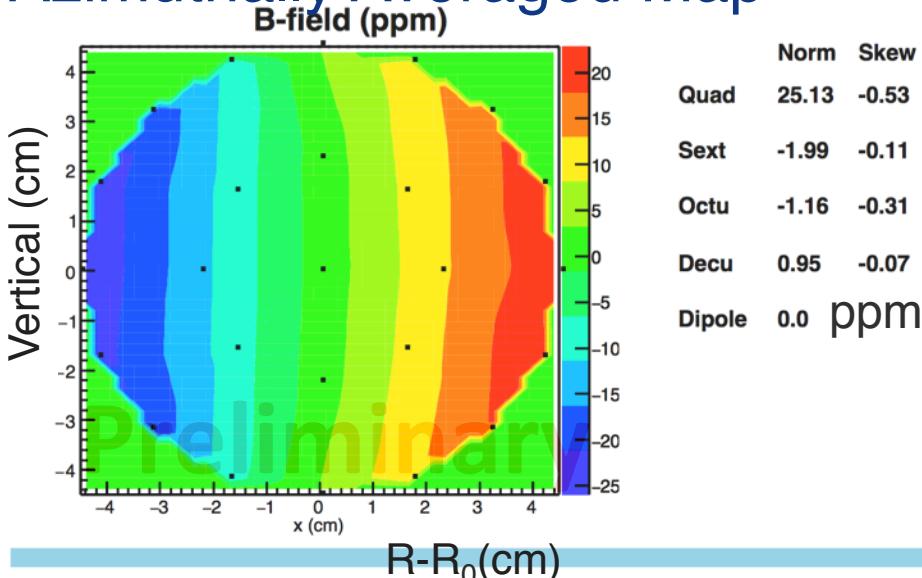
$\sim 10 \text{ ppm}$ achieved this week
Extremely Promising!

Early measurements demonstrate that we are off to a great start

Dipole Moment



Azimuthally Averaged Map



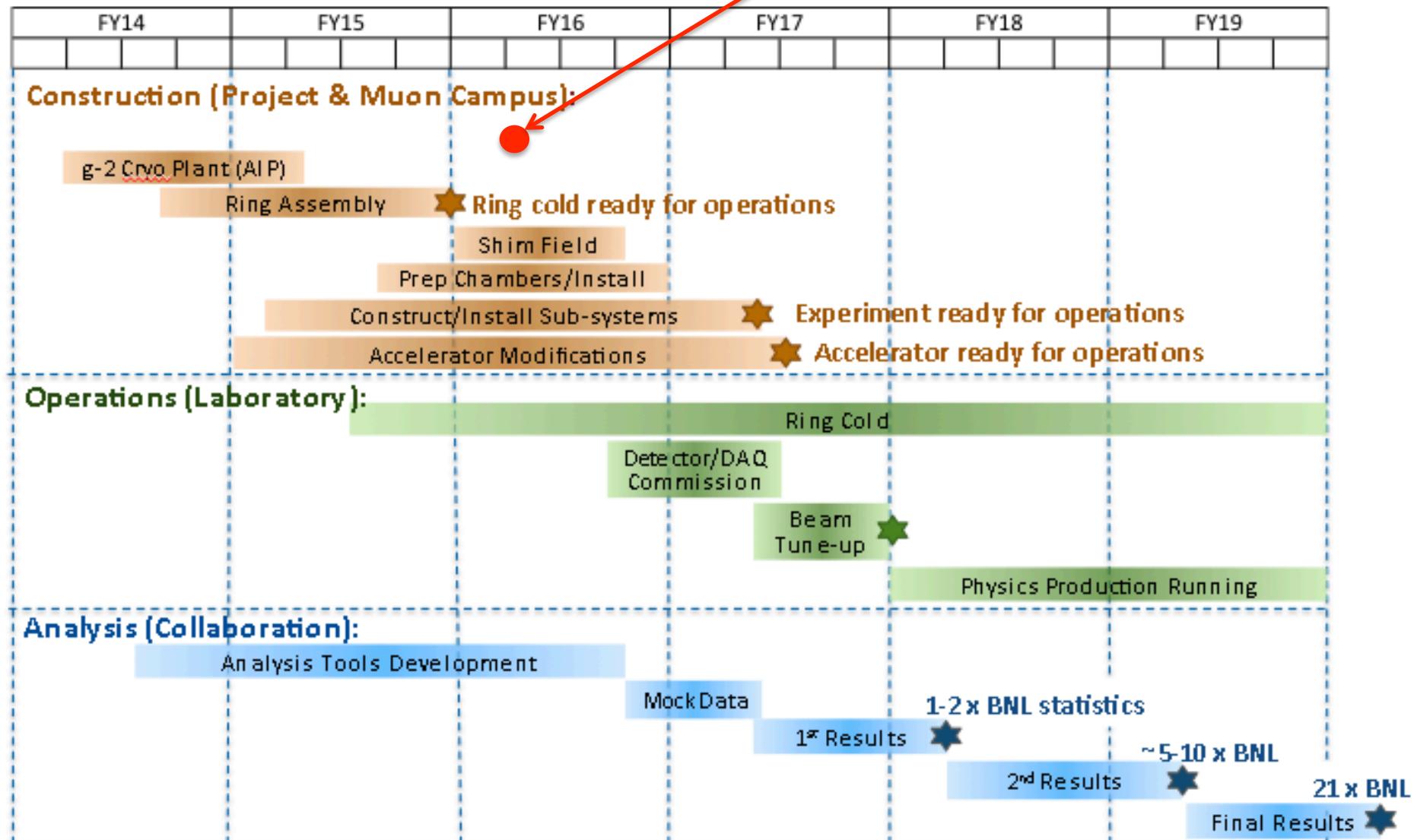
- Achieved Calibration of the shimming Knobs
- Developed Techniques to address remaining non-uniformities
- Embarking on systematic effort to smooth discontinuities

plot courtesy J. Grange



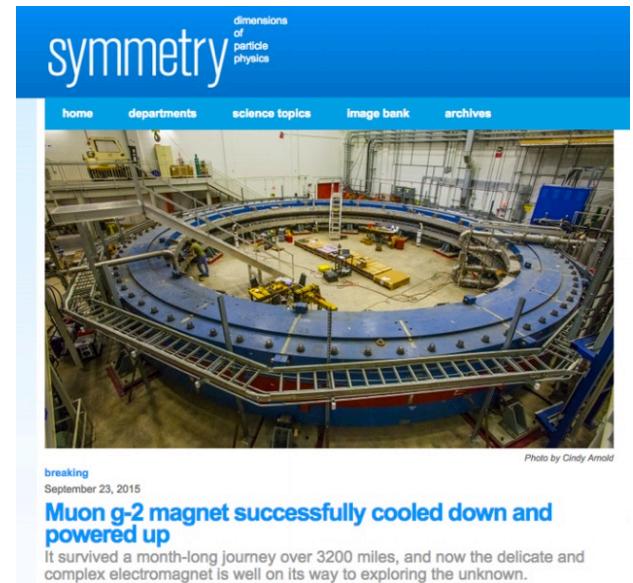
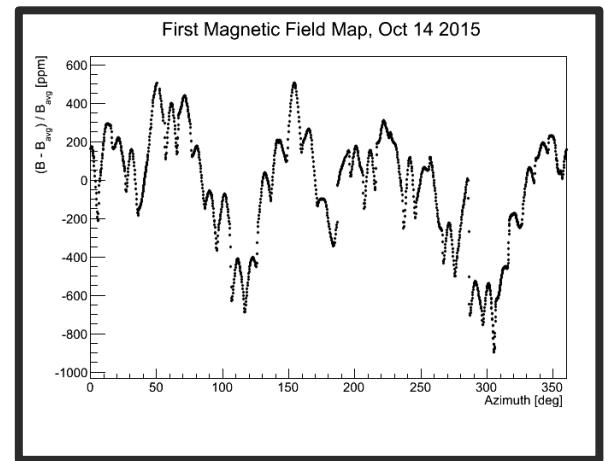
Timeline going forward

You Are Here



Summary

- Significant Theory Efforts
 - e^+e^- measurements improving HVP uncertainty
 - Significant Progress on the Lattice
- Fermilab experiment is cold and powered
 - Magnetic field measurements 2015
 - Systematic shimming through Spring
 - Installation in 2nd half of 2016
 - Muons in 2017
- These are exciting times!





Thank You!